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Multi-objective design and optimisation of urban energy systems

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1 Introduction

When considering the energy flows of a country like Switzerland, more than 50% of the energy consumption is devoted to the production of heating services at rather low temperature level (less then 100 $\deg C$. Furthermore, when considering that about 75% of the population leaves in urban areas, the design of urban energy systems is one of the most important problem when considering the problem of CO_2 mitigation (in Switzerland about 25 % of the CO_2 emissions comes from the heating requirements of households).

A district energy systems provides heating, hot water, cooling and electricity to two or more buildings. They include the energy conversion technologies (preferably polygeneration energy conversion technologies) together with the distribution networks. Unlike district heating systems, that provide only heating, district energy systems have not yet been much studied. District heating systems are often implemented when excess heat, from a geothermal source or from the combustion of waste for instance, is to be recycled. In the latter case, the system can also be designed to generate electricity. The majority of the literature on district heating systems concerns the optimization (mainly financial) of the operation strategies and/or the thermo-economic optimization of the energy conversion technologies ([20, 2, 27, 1, 21, 24, 15]), as well as the energetic and/or exergetic performance of the complete district heating system ([17, 5]). In nearly all of these papers, the distribution network of the analysed district heating system already exists. Its design is only seldom mentioned, and if ever, then in a very simplified manner. One reason for the researchers not to be more interested in the design of distribution networks could be the believe by some of them that the design of the distribution network is anyway solved by politicians and urban planners, without involving any quantitative support [1], and that it is therefore useless to include the design of the distribution network when studying the thermo-environomic optimization of district energy systems. However, it is the believe of the authors that politicians and urban planners could be interested in using quantitative support, if they had the tools to do so. Söderman has studied the design of distributed energy systems [?] and developed a tool for decision makers. However the study doesn't take into account the temperature levels at which the energy services have to be delivered. Friedler et al. studied process synthesis and optimization for the chemical industry [11, 12], and it would be possible, considering some analogies and modifications, to adapt his method to district energy systems. In fact his works do not take into account any spatial constraints regarding the location of the technologies. Besides, the chemical processes that are designed are of the continuous type, whereas district energy systems are more related to a batch type operating mode (the energy requirements vary from one period to the other).

The method presented combines the design of the network together with the definition of the sizes and the operating strategies of the technologies that are best suited to meet the energy requirements of the district. The method takes into account the *spatial* and *temporal* aspects that are characteristic of district energy systems, as well as the temperature levels at which the energy services are requested. It addresses the following question: How shall a district energy system, a system that comprises the energy conversion technologies that transform the primary energy into the requested energy form (heating, cooling, electricity and hot water), and the distribution network from the plant to the customers, be designed, to minimze the overall costs and the CO_2 emissions while delivering the hourly energy services requested by the customers ?

Because it combines spatial (location of the buildings) and temporal (consumption profiles) aspects, the design of a polygeneration district energy system is a complex problem. The number of possible configurations is very high since it concerns the identification of the energy conversion plant location, the different ways of connecting the buildings together with the size and the type of the energy conversion units. In addition, the performance of the system requires the definition of the optimal operating strategy that accounts for the consumption profiles of the different sevices (electricity, heating, cooling) that vary during the day, and from day to day in a stochastic manner.

The method developped (fig. 1) comprises a structuring phase in which all the relevant data regarding the district considered are gathered, an optimization phase in which the optimal district energy system is designed, and a post-processing phase in which the total costs and CO_2 emissions of the the system are computed. Due to the complexity of the analysed problem, the opimization phase is decomposed in a master optimization and a slave optimization.

2 Structuring phase

Having defined the system boundaries, the structuring phase is the phase in which all the relevant information regarding the district for which an energy system needs to be designed, are gathered, structured, and put in the required form to be used in the optimization phase.

Definition of the list of available energy sources
A comprehensive analysis of the available energy sources in the district will be realised. These include fossil and renewable energy sources such as wind, waste, sewage water, lakes, rivers, sun, geothermal energy,... For each energy source, the necessary parameters have to be gathered in order to assess the energy conversion integration. These concern both the quantity available and the quality such as the temperature level or the wind speed.

Energy consumption profiles including power and temperature levels
For each building, the energy consumption profiles for the different energy services need to be known. For the thermal energy requirements (heating, hot water and cooling) it is important to know the power required as well as its required temperature level. Besides, for all energy services the *power level* is of utmost importance to design the size of the energy conversion technologies. Therefore, the profiles of the energy requirements, for *all* energy services, are best given in average hourly rates for each period (in kW), together with the duration of each period in hours. Considering the stochastic nature of the inhabitants' behaviour and of the meteorological conditions, typical days representing the operating conditions to be considered for the design will be defined. In many cases, a six period profile including a day and a night period for summer, winter and mid-season, can already be considered sufficient.

Routing algorithm
The system has to fit in an existing geographical area. Therefore constraints such as buildings location, roads layout, space constraints in existing underground channels,... have to be taken into account when computing

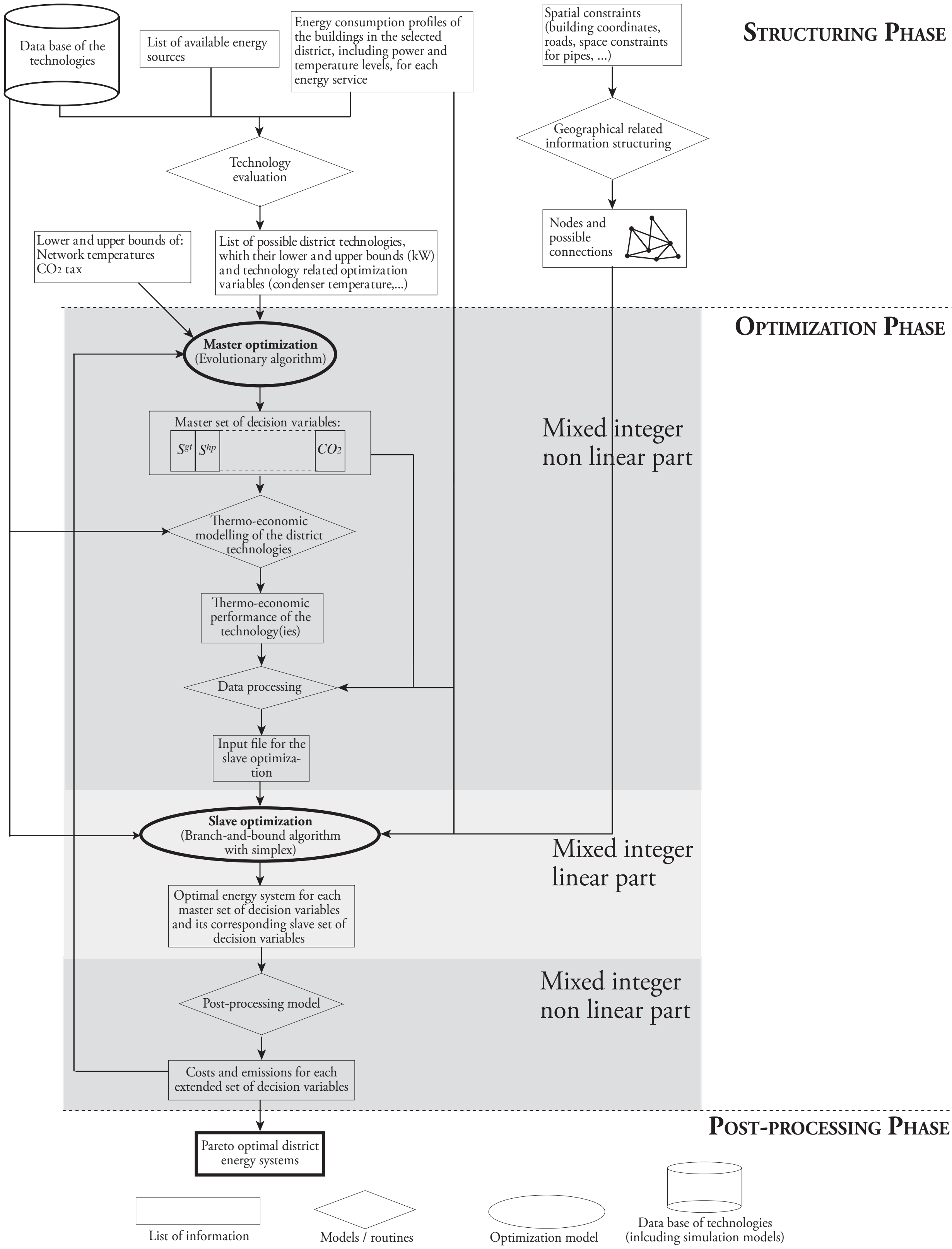


Figure 1: Method developed to solve the district energy system design and operation problem

the possible layout of the network. Typically, a pipe will not be allowed to follow the shortest path between two buildings, but has to follow certain routes as shown in figure 2.

Technology data base

The *technology data base* includes centralised and decentralised (back-up) energy conversion technologies. Centralised technologies are the energy conversion technologies that *are connected* to the distribution networks and provide heating, hot water, cooling and electricity to the different customers in the district via the networks. Decentralised technologies are implemented directly in the building they serve, in case the building is not connected to the network or when the district energy system cannot meet the energy requirements of this building (for instance if the temperature level at which the heat is required by a single given building is above the temperature level of the network, or if the building is located too far away from the rest of the buildings to justify a connection). The data base includes the thermo-economic simulation models of the different energy conversion technologies. Thermo-economic models means that the model will compute as a function of the services required and the size of the equipment, the thermodynamic performances and the corresponding environmental impact or emissions, together with an estimate of the economical costs, including operating, maintenance and investment costs.

Considering the list of available energy sources, together with the energy consumption profiles (including the temperature and power levels), the *Technology evaluation* tool analyses the data base to establish a list of possible technologies that can be used in the analysed district. For instance, if the district is located in the vicinity of a lake or a river, heat pumps will be added in the list. Besides, if geothermal energy is available, a steam turbine or an organic Rankine cycle can be implemented. On contrario, considering wind mills in cities featuring no favourable wind conditions will not lead to a reasonable solution. Or else, if the maximum average hourly electricity rate amounts to 4000 kW for instance, no gas turbine combined cycle will be proposed.

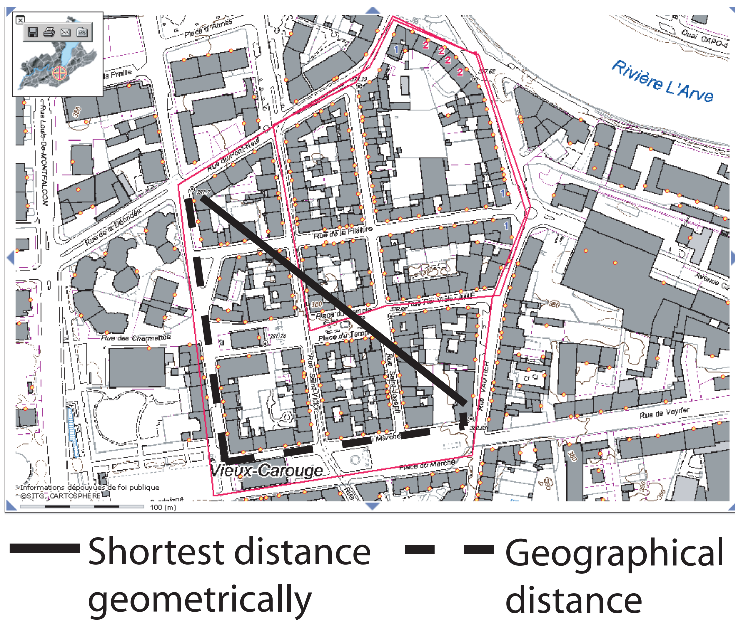


Figure 2: Difference between the geographical route that has to be followed to connect two buildings, and the shortest distance geometrically [25]

3 Optimization phase

The optimization phase aims at combining in an optimal manner the ressources, the energy conversion units in order to satisfy the requirements in the area. The optimization problem is defined on figure 1. It concerns the following decision variables:

1. Centralized and decentralized energy conversion technologies:
   - Type of the unit
   - Installed size
   - Location in the area
   - Unit specific operating conditions
   - Operation strategy (i.e. level of usage at a given time)
2. District heating and cooling networks:
   - Existence and size of the pipes in the energy distribution networks (for heating and cooling)
   - Supply and return temperatures of the distribution networks in the different periods
   - Flows in each pipe in each period

A thermo-economic model will compute the performances of the system. This is done by solving first the thermodynamic performances of the system and then estimating the corresponding investment costs. (*Je ne comprends pas très bien ce que cette phrase vient faire ici.*)

A thermo-economic multi-objective optimization problem will then be solved. The two objectives are the yearly costs (including investment, maintenance and operation) and yearly CO_2 emissions (operation). The results of the multi-objective optimization problem defines the Pareto optimal frontier of the system. in this curve, each point corresponds to one system configuration including the network design, the equipment and the operation strategy for each of the units.

4 The post-processing phase

The optimisation phase results in a list of urban energy systems configurations whose performances have to be evaluated so that the stake-holders will make their final choice. In the post-processing phase, the performances of each configuration are evaluated and a multi-criteria analysis will be realised. Using the calculated performance indicators, decision-makers will apply criteria such as :

- the available budget,
- the maturity of the technology,
- the CO_2 emissions reduction targets,
- the degree of usage of renewable energy,
- the sensitivity analysis on some parameters,
- the acceptance of the population for given solutions,
- the implementation delays,
- the political program,
- ...

The multi-criteria analysis will be based on the weight given to each of the performance indicators by the stake-holders. The success of this phase strongly relies on a close collaboration between all the decision-makers, stake-holders and engineers.

5 Resolution strategy of the optimization phase

Due to the complexity of the problem, a specific optimization strategy is needed. The optimization problem involves both discrete and continuous variables and the models may be non linear. Therefore the problem to be solved is a mixed integer non linear programming (MINLP) multi-objective optimization problem.

The optimization problem is decomposed into two parts, a non linear part, which is defined as a *multi-objective* master optimization problem solved by an evolutionary algorithm and a mixed integer linear part, which is defined as a *single-objective* slave optimization problem solved by a branch-and-bound algorithm combined with the simplex method. It is therefore necessary to divide the variable set into two sub-sets in such a way that the network design and optimization can be solved linearly in a consistent manner with respect to the non linear nature and the multi-objective purpose of the master problem. The decomposition strategy is mainly justified by the non linear nature of the problem and the number of decision variables, especially the discrete variables required to define the configuration of the netwrok. The non linear nature of the problem makes the application of branch-and-bound strategies impractical while the combinatorial nature of the problem makes the use of evolutionary algorithm also impractical. In fact, the application of evolutionary algorithm would futhermore require a careful analysis of the degree of freedom of the problem and the definition of a very efficient non linear solving procedure. The branch-and-bound algorithm are typically used for solving network optimization problems like for instance the Traveling Salesman Problem or the Assignment Problem [22]-[23], and show very good convergence properties. It is therefore chosen to solve the network design and optimization. The branch-and-bound algorithm is not at all suited when non linear issues like the efficiencies of given technologies for instance are implied. Considering that the algorithms used to solve mixed integer linear problems (like the branch-and-bound algorithm) The purpose of the decomposition is therefore to combine the advantages of both optimization algorithms (the ability of the evolutionary algorithm to solve any type of optimization without requiring too drastic simplifications, and the speed of the branch-and-bound algorithm) together with the advantages of the separation of the decision variables.

The set of decision variables handled by the master optimization will be called hereafter the *master set* of decision variables, and the set of decision variables solved in the slave optimization will be called the *slave set* of decision variables. The combination of both sets of decision variables is the *extended set* of decision variables.

Beside the master and the slave optimization algorithms, the constraints of the optimization phase will model the thermo-economic performances of the district technologies. In addition to the mathematical nature of the decomposition, the decision variable set partitioning has been realised considering the physical meaning of the variables. The master set of decision variables is directly linked to the type and size of the technologies and given as input to the thermodynamic models in order to compute the performances of the technologies (efficiencies, mass flow rates,...). The results of the thermodynamic models, together with further decision variables of the master set (the network supply temperature and the temperature difference of the network in the decentralized heat pumps), the consumption profiles and the possible connections are used to compute the parameters of the slave optimization. The slave optimization then computes the slave set of decision variables that defines the optimal energy system configuration and its operation, as a function of the given master set of decision variables.

The multi-objective evolutionary optimizer used for this study was developed at the Industrial Energy Systems Laboratory at the Ecole Polytechnique Fédérale de Lausanne [16]. This optimizer uses the technique of the evolutionary algorithms to compute the trade-offs between multiple objectives. In our case, two ob-

Decision variable	Lower bound - upper bound
District energy conversion technologies	Minimum available size (market size) for the technology - Minimum between the maximum requirements and the maximum available market size
Specific technology related, optimization parameters (if any)	
Supply temperature for the heating network for each period	40°C - 120°C
Return temperature for the heating network for each period	30°C - supply temperature of the respective period
Supply temperature for the cooling network for each period	6°C - 20°C
Return temperature for the cooling network for each period	Supply temperature of the respective period - 22°C
CO_2 weighting factor:	0 CHF/kWh - 0.50 CHF/kWh

Table 1: Lower and upper bounds of the continuous decision variables optimized by the master optimizer

jectives have to be minimized: the costs (including operation and investment) and the CO_2 emissions of the system. In order to find the optimal configurations with the best performances in terms of CO_2 emissions and costs, the evolutionary algorithm creates a population of individuals (a set of master decision variables) by choosing randomly, for each individual, a set of values (genome) representing the decision variables. The "scores" or performances of each individual are then computed by solving the slave optimization problem. New individuals are then selected based on the scores of the existing individuals, using a set of combination operators such as mutation and crossover. After the evolution process is continued sufficiently, keeping the best individuals in the non-dominated set (according to CO_2 emissions and costs), the optimal solutions can be found. This multi-objective strategy results in an estimation of the Pareto optimal frontier (hereafter Pareto curve) that represents the set of optimal points that can be considered to be optimal in terms of one or both of the two objectives. Each point of this curve corresponds to one configuration of the system and the optimal way of operating it on a yearly basis.

6 Mathematical formulation of the optimization phase

6.1 The master optimization

6.1.1 Objective function and decision variables

The inputs of the master optimization are the list of decision variables with their lower and upper bounds. These decision variables include: binary variables for the choice of the district energy conversion technologies, continuous variables for the size of the district energy conversion technologies (S_{ct} and S_{ht}), various technology related parameters (like the condenser temperature for heat pumps for instance), the temperatures of the networks ($T_{\mathrm{hs},t}$, $T_{\mathrm{hr},t}$, $T_{\mathrm{cs},t}$ and $T_{\mathrm{cr},t}$) and the CO_2 weighting factor. Regarding the temperatures, the method allows to optimize the supply and return temperatures of each network for each period independently. The lower and upper bounds of the *continuous* variables are given in table 1.

In the problem formulation, the ranges of all the continuous decision variables have been normalised to vary between 0 and 1, in order to homogenize the ranges of the different decision variables and therefore ensure a better covering up of the search space.

6.1.2 Constraints and parameters

The constraints of the master optimization include the models of the district energy conversion technologies, the equations of the data processing routine, as well as some values needed to define the slave optimisation problem.

The parameters include:

- the parameters used in the models of the district energy conversion technologies (exergetic efficiency of heat pumps or isentropic efficiencies of compressors for instance),
- the parameters used in the data processing routine (velocity of the water in the pipes, specific heat of water,....),
- the parameters of the slave optimization (fix and proportional costs of the pipes or individual back-up energy conversion technologies for instance).

Except for the thermodynamic parameters such as the specific heat of water, or else parameters such as the velocity of the water in the pipes, the values of the parameters change from district to district.

6.2 The slave optimization

6.2.1 Objective function and decision variables

The objective function minimises the annual operating costs and the annual investment costs, considering the possible income I^{el} of the excess electricity generated by the district energy conversion technologies. The annual operating costs include the costs for the natural gas, the grid electricity, the oil and the CO_2 emissions taxes. The annual investment costs include the costs for the pipes, circulation pumps, heat-exchangers and individual back-up energy conversion technologies (air/water heat pumps, water/water heat pumps, boilers and chillers). The slave optimisation is therefore formulated as equation 1.

$$\min\left(C^{\mathrm{gas}}+C^{\mathrm{grid}}+C^{\mathrm{oil}}+C^{\mathrm{CO_2}}+C^{\mathrm{pipes}}+C^{\mathrm{pump}}+C^{\mathrm{hex}}+C^{\mathrm{aw}}+C^{\mathrm{ww}}+C^{\mathrm{boiler}}+C^{\mathrm{chiller}}-I^{\mathrm{el}}\right) \quad [\mathrm{CHF/year}] \tag{1}$$

6.2.2 Constraints of the slave optimization

The following types of constraints are considered in the slave optimization sub-problem:

1. Energy balances at each node
   - First principle[1] thermal energy balances
   - Heat cascades
   - Electrical energy balances
2. Mass balances in the network
3. Connections of nodes and implementation/location of the technologies (district and back-up technologies)

[1]The term *First principle* refers to the thermodynamic principles.

4. Performance functions (costing and CO_2 emission)
5. Empirical (engineer knowledge based) constraints

Figures 3 and 4 show respectively the superstructure of the network and the superstructure considered at each node as well as the decision variables considered in the slave optimization.

6.2.3 First principal energy balances

1. Energy balances at the consumer's place (see also figure 4)
   Energy balances are defined for heating and hot water requirements (indices H and HW in equation 2), as well as for cooling requirements (index C in equation 3). These energy balances link the energy required by a node, with the energy provided by the network $\dot{Q}^{\text{build}}_{\text{hs},t,k}$, respectively $\dot{Q}^{\text{cons}}_{C,t,k}$, or the energy provided by decentralized technologies ($\dot{Q}^{\text{ww}}_{t,k}$, $\dot{Q}^{\text{aw}}_{t,k}$, or $\dot{Q}^{\text{boiler}}_{t,k}$ for heating, and $\dot{Q}^{\text{chiller}}_{t,k}$ for cooling). $\dot{Q}^{\text{loss}}_{t,k}$ represents all the losses that occur in the heating distribution network, and that have to be compensated by the district energy conversion technologies located at node k, if any (heat "losses" have been neglected for the cooling network).
   Heating and hot water:
   $$\dot{Q}^{\text{cons}}_{H,t,k} + \dot{Q}^{\text{cons}}_{HW,t,k} + \dot{Q}^{\text{loss}}_{t,k} = \dot{Q}^{\text{build}}_{\text{hs},t,k} + \dot{Q}^{\text{aw}}_{t,k} + \dot{Q}^{\text{ww}}_{t,k} + \dot{Q}^{\text{boiler}}_{t,k} \qquad \forall t,k \tag{2}$$
   Cooling:
   $$\dot{Q}^{\text{cons}}_{C,t,k} = \dot{Q}^{\text{build}}_{\text{cs},t,k} + \dot{Q}^{\text{chiller}}_{t,k} \qquad \forall t,k \tag{3}$$
2. Energy balances between the consumers and the network (see also figure 3)
   For each building connected to the network, the following balances relate the energy supplied by the networks (heating and cooling) to the building, with the mass flow rate of water flowing from the networks to the buildings. In the following equations, $T_{\text{hs},t}$ and $T_{\text{hr},t}$ are the supply, respectively return, temperatures of the heating network, and $T_{\text{cs},t}$ and $T_{\text{cr},t}$ the supply and return temperatures of the cooling network.
   Heat supplied by the network to the building:
   $$\dot{Q}^{\text{build}}_{\text{hs},t,k} = \dot{M}^{\text{build}}_{\text{hn},t,k} \cdot cp^{\text{liq}}_{H_2O} \cdot (T_{\text{hs},t} - T_{\text{hr},t}) \forall t,k \tag{4}$$
   Heat supplied by the heating network to the water/water heat pump in case individual back-up water/water heat pumps locally increase the temperature level of the network:
   $$\dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k} = \dot{M}^{\text{hn\_ww}}_{\text{hn},t,k} \cdot cp^{\text{liq}}_{H_2O} \cdot (T_{\text{hs},t} - T_{\text{hr},t}) \forall t,k \tag{5}$$
   with
   $$\dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k} = \left(1 - \frac{1}{COP^{\text{ww}}_{t,k}}\right) \cdot \dot{Q}^{\text{ww}}_{t,k} \qquad \forall t,k \tag{6}$$
   and
   $$COP^{\text{ww}}_{t,k} = \eta^{hp} \cdot \frac{T_{Hs,t,k} + \Delta T}{T_{Hs,t,k} - T_{\text{hr},t}} \forall t,k \tag{7}$$
   where η^{hp} is the exergetic efficiency of the heat pump, $T_{Hs,t,k}$ is the supply temperature of the hydronic circuit in the building, and $T_{\text{hr},t}$ the return temperature of the heating network.
   Cooling supplied by the network to the building:
   $$\dot{Q}^{\text{build}}_{\text{cs},t,k} = \dot{M}^{\text{build}}_{\text{cn},t,k} \cdot cp^{\text{liq}}_{H_2O} \cdot (T_{\text{cr},t} - T_{\text{cs},t}) \forall t,k \tag{8}$$

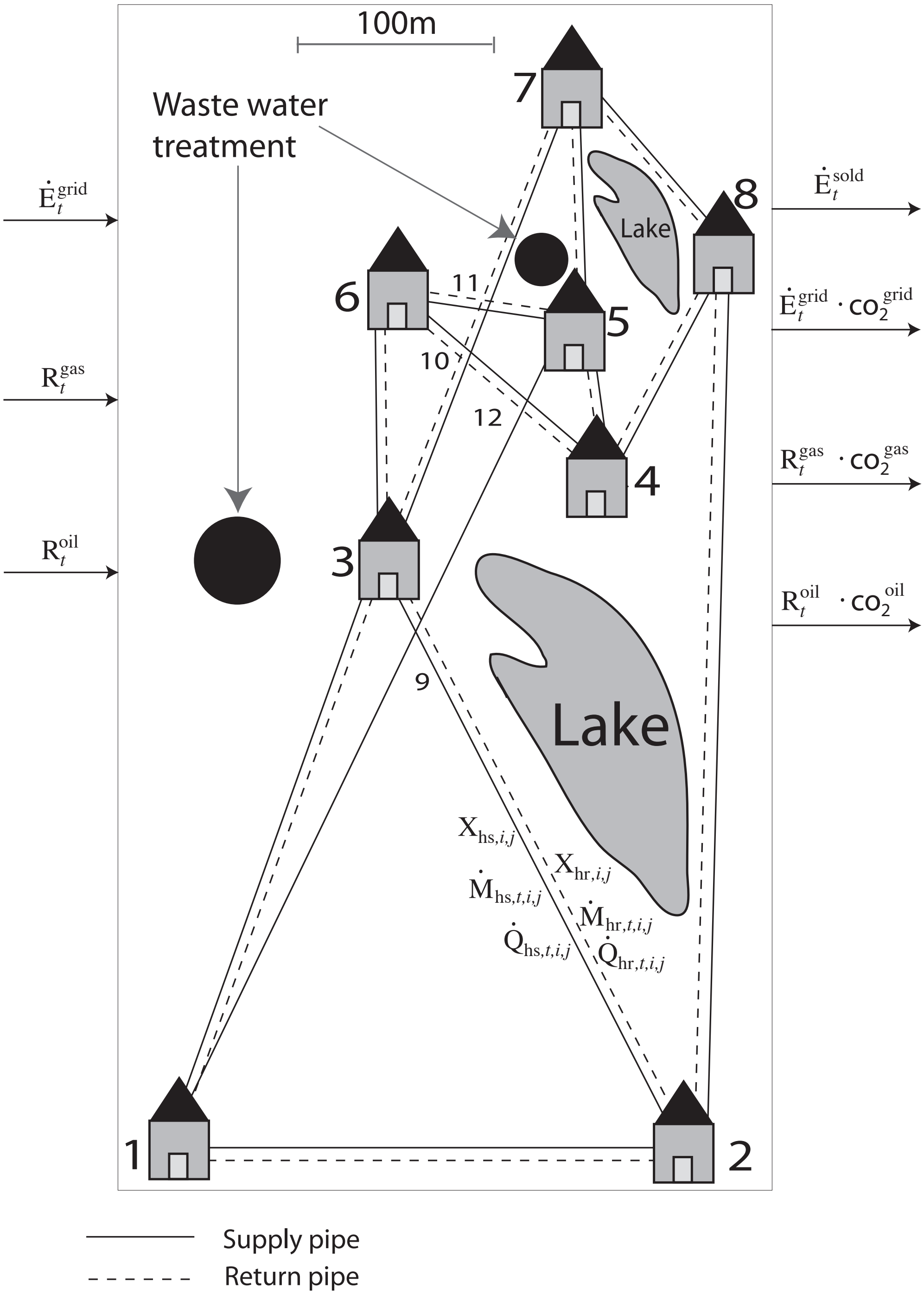


Figure 3: Structure of the district (the plain lines between the buildings refer to the supply part of the distribution network and the dotted lines to the return part)

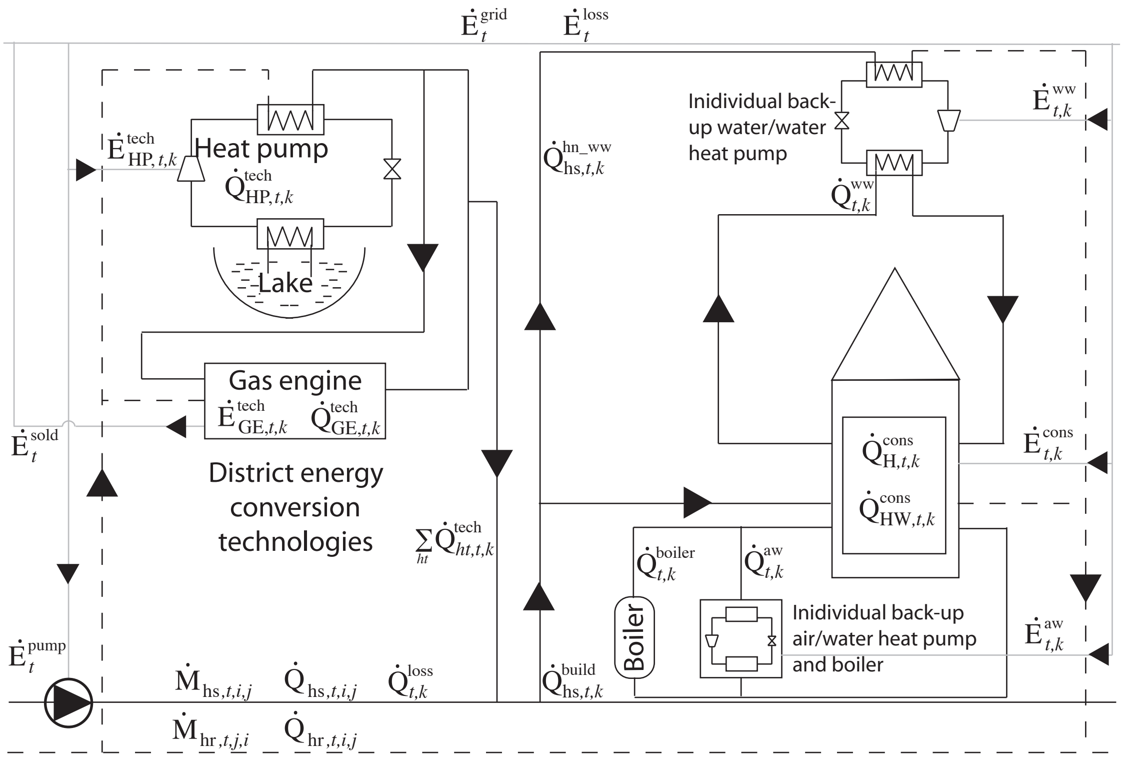


Figure 4: Superstructure of a node (the plain lines refer to the supply part of the distribution network and the dotted lines to the return part)

3. Energy balances at the plant node[2]
   Heat provided by the district technology ht at node k to the heating network:

$$\dot{Q}^{\text{tech}}_{ht,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{hn},t,k} \cdot \Delta T_{ht} \qquad \forall t, ht, k \tag{9}$$

   Heat provided by the sum of all the technologies at node k to the heating network:

$$\sum_{ht} \dot{Q}^{\text{tech}}_{ht,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{hn},t,k} \cdot (T_{\text{hs},t} - T_{\text{hr},t}) \qquad \forall t, k \tag{10}$$

   Cooling load provided by the technology ct at node k to the cooling network:

$$\dot{Q}^{\text{tech}}_{ct,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{cn},t,k} \cdot \Delta T_{ct} \qquad \forall t, ct, k \tag{11}$$

   Cooling load provided by the technologies at node k to the cooling network:

$$\sum_{ct} \dot{Q}^{\text{tech}}_{ct,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{cn},t,k} \cdot (T_{\text{cr},t} - T_{\text{cs},t}) \qquad \forall t, k \tag{12}$$

4. Energy balances of a node
   The following energy balances are defined at each node for the heating and cooling networks between to the energy leaving the node on one side (left hand side of the = sign), and the energy arriving at the node, consumed by the node, and provided by the node if a district energy conversion technology is located at that node, on the other side (right hand side of the = sign).
   Heating supply network hs:

$$\sum_{(k,j)} \dot{Q}_{\text{hs},t,k,j} = \sum_{(i,k)} \dot{Q}_{\text{hs},t,i,k} - (\dot{Q}^{\text{build}}_{\text{hs},t,k} + \dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k}) + \dot{Q}^{\text{tech}}_{ht,t,k} \qquad \forall t, k \tag{13}$$

   Cooling supply network cs:

$$\sum_{(k,j)} \dot{Q}_{\text{cs},t,k,j} = \sum_{(i,k)} \dot{Q}_{\text{cs},t,i,k} - \dot{Q}^{\text{build}}_{\text{cs},t,k} + \dot{Q}^{\text{tech}}_{ct,t,k} \qquad \forall t, k \tag{14}$$

5. Heat losses
   The heat losses for each period in the heating network[3], are computed by multiplying the specific heat losses (equation **??**) with the total length of the network:

$$\dot{Q}^{\text{loss}}_{t} = \sum_{(i,j)} Dist_{i,j} \cdot X_{\text{hs},i,j} \cdot \dot{q}^{\text{loss}}_{t} \qquad \forall t \tag{15}$$

   In order to be able to integrate these heat losses to the energy balance given in equation 2, they are attributed as an additional energy requirement to the node hosting the district energy conversion technologies (therefore $\sum_{k} \dot{Q}^{\text{loss}}_{t,k} = \dot{Q}^{\text{loss}}_{t}$).

6.2.4 Heat cascade constraints

From the simulation models of the technologies and of the heat requirement profiles, the corrected temperatures are computed assuming a minimum approach temperature in the heat exchanger. the corrected temperature are then ranked to allow for the calculation of heat cascades considering the corresponding

[2]The term *plant* is used to designate a node where district energy conversion technologies are implemented. A given node can be simultaneously a plant node and a consumer node as shown on figure **??**.

[3]The heat losses in the cooling network have been neglected.

temperature intervals. The heat cascades define a set of linear constraints in the system. It includes:
Heat cascade between the district heating technologies and the heating network for each temperature interval:

$$\sum_{ht}\sum_{k}\dot{Q}^{\text{tech}}_{ht,t,k,d} + \dot{Q}^{\text{tn}}_{\text{hs},t,(d-1)} - \dot{Q}^{\text{tn}}_{\text{hs},t,d} \geq \dot{Q}^{\text{net}}_{\text{hs},t,d} \qquad \forall t, d \tag{16}$$

with $\dot{Q}^{\text{tn}}_{\text{hs},t,k,(d-1)}$ the excess heat transferred from temperature interval $d-1$ to interval d and $\dot{Q}^{\text{net}}_{\text{hs},t,d}$ the heat required by the heating network in interval d.

Heat cascade between the heating network and the buildings for each temperature interval:

$$\dot{Q}^{\text{net}}_{\text{hs},t,d} + \sum_{k}\dot{Q}^{\text{nb}}_{\text{hs},t,k,(d-1)} - \sum_{k}\dot{Q}^{\text{nb}}_{\text{hs},t,k,d} \geq \sum_{k}(\dot{Q}^{\text{req}}_{H,t,k,d} + \dot{Q}^{\text{req}}_{HW,t,k,d}) \qquad \forall t, d \tag{17}$$

with $\sum_{k}\dot{Q}^{\text{nb}}_{\text{hs},t,k,(d-1)}$ is the heat from the heating network transferred from interval $d-1$ to interval d, and $\sum_{k}(\dot{Q}^{\text{req}}_{H,t,k,d} + \dot{Q}^{\text{req}}_{HW,t,k,d})$ the sum of all the heating and hot water requirements of the district in interval d.

The link between the heat cascade defined in equation 16 and the heat cascade defined in equation 17 is ensured by the balancing term $\dot{Q}^{\text{net}}_{\text{hs},t,d}$ and its corresponding mass flow rate (given by equation 9 and/or 10), which remains constant for all temperature intervals.

Heat cascade between the district cooling technologies and the cooling network for each temperature interval:

$$\sum_{ct}\sum_{k}\dot{Q}^{\text{tech}}_{ct,t,k,d} + \dot{Q}^{\text{tn}}_{\text{cs},t,(d-1)} - \dot{Q}^{\text{tn}}_{\text{cs},t,d} \geq \dot{Q}^{\text{net}}_{\text{cs},t,d} \qquad \forall t, d \tag{18}$$

Heat cascade between the cooling network and the buildings for each temperature interval:

$$\dot{Q}^{\text{net}}_{\text{cs},t,d} + \sum_{k}\dot{Q}^{\text{nb}}_{\text{cn},t,k,(d-1)} - \sum_{k}\dot{Q}^{\text{nb}}_{\text{cn},t,k,d} \geq \sum_{k}\dot{Q}^{\text{req}}_{C,t,d,k} \qquad \forall t, d \tag{19}$$

6.2.5 Electricity balances

$$\sum_{k}\dot{E}^{\text{cons}}_{t,k} + \dot{E}^{\text{pump}}_{t} + \sum_{k}(\dot{E}^{\text{aw}}_{t,k} + \dot{E}^{\text{ww}}_{t,k} + \dot{E}^{\text{chiller}}_{t,k}) + \dot{E}^{\text{loss}}_{t} + \dot{E}^{\text{sold}}_{t} = \dot{E}^{\text{grid}}_{t} + \sum_{ht}\dot{E}^{\text{tech}}_{ht,t,k} \qquad \forall t \tag{20}$$

Electricity generated by the district technologies:

$$\dot{E}^{\text{tech}}_{ht,t,k} = \frac{\dot{Q}^{\text{tech}}_{ht,t,k}}{\epsilon^{ht}_{\text{th}}} \cdot \epsilon^{ht}_{\text{el}} \qquad \forall ht, t, k \tag{21}$$

If a district energy conversion technology requires electricity (such as a heat pump), its electric efficiency has been computed such that $\epsilon^{ht}_{\text{el}} < 0$. Therefore $\dot{E}^{\text{tech}}_{ht,t,k}$ is also < 0[4].

[4]For instance, if a district heat pump has a COP of 3, $\epsilon^{ht}_{\text{el}} = -0.33$ and $\epsilon^{ht}_{\text{th}} = 1$. Therefore, $\dot{E}^{\text{tech}}_{ht,t,k} = -0.33 \cdot \frac{\dot{Q}^{\text{tech}}_{ht,t,k}}{\epsilon^{ht}_{\text{th}}}$

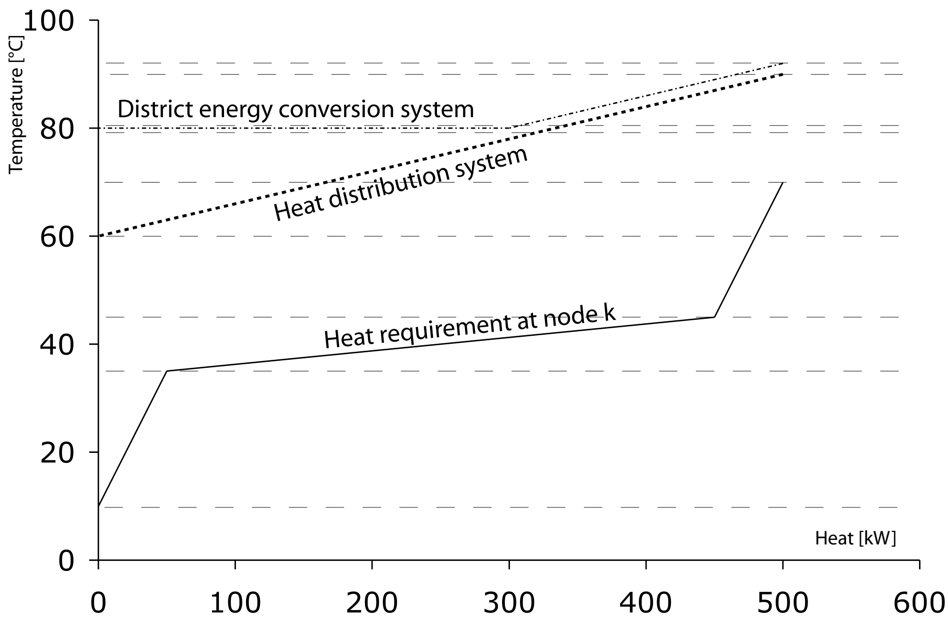


Figure 5: Heat cascades at a given node : the first heat cascade concerns the energy conversion and the heat distribution system, the second concerns the heat distribution system and the heat requiremen of the node.

Electricity losses are computed considered the grid efficiency ϵ^{grid}:

$$\dot{E}_t^{\text{loss}} = (1 - \epsilon^{\text{grid}}) \cdot \sum_{ht} \dot{E}_{ht,t}^{\text{exp}} \qquad \forall t \tag{22}$$

Electricity required for the decentralized water/water heat pump(s):

$$\dot{E}_{t,k}^{\text{ww}} = \frac{\dot{Q}_{t,k}^{\text{ww}}}{COP_{t,k}^{\text{ww}}} \qquad \forall t, k \tag{23}$$

with $COP_{t,k}^{\text{ww}}$ given by equation 7

Electricity required for the decentralized air/water heat pump(s):

$$\dot{E}_{t,k}^{\text{aw}} = \frac{\dot{Q}_{t,k}^{\text{aw}}}{COP_{t,k}^{\text{aw}}} \qquad \forall t, k \tag{24}$$

with

$$COP_{t,k}^{\text{aw}} = \eta^{hp} \cdot \frac{T_{Hs,t,k} + \Delta T}{T_{Hs,t,k} - T^{\text{atm}}} \forall t, k \tag{25}$$

Electricity required for the individual back-up chiller(s):

$$\dot{E}_{t,k}^{\text{chiller}} = \frac{\dot{Q}_{t,k}^{\text{chiller}}}{COP_{t,k}^{\text{chiller}} - 1} \qquad \forall t, k \tag{26}$$

Electricity required by the network circulation pumps:

$$\dot{E}_t^{\text{pump}} = \frac{\left\{ \sum_{i,j} \left(\dot{M}_{\text{hs},t,i,j} + \dot{M}_{\text{hr},t,i,j} + \dot{M}_{\text{cs},t,i,j} + \dot{M}_{\text{cr},t,i,j} \right) \cdot Dist_{i,j} \right\} \cdot p_t^{\text{drop}}}{\rho} \qquad \forall t \tag{27}$$

6.2.6 Mass balances

Mass balances are defined at each node for both the supply and the return networks. They link the mass flow rate of water leaving the node (left hand side of the = sign in equations 28 and 29), with the mass flow rate of water arriving at the node, flowing through the building located at the node, and coming from the building at node k if a district energy conversion technology is located at that node (right hand side of the = sign).

Heating supply network:

$$\sum_{(k,j)} \dot{M}_{\text{hs},t,k,j} = \sum_{(i,k)} \dot{M}_{\text{hs},t,i,k} - (\dot{M}_{\text{hn},t,k}^{\text{build}} + \dot{M}_{\text{hn},t,k}^{\text{hn\_ww}}) + \dot{M}_{\text{hn},t,k}^{\text{tech}} \qquad \forall t, k \tag{28}$$

Cooling supply network:

$$\sum_{(k,j)} \dot{M}_{\text{cs},t,k,j} = \sum_{(i,k)} \dot{M}_{\text{cs},t,i,k} - \dot{M}_{\text{cn},t,k}^{\text{build}} + \dot{M}_{\text{cn},t,k}^{\text{tech}} \qquad \forall t, k \tag{29}$$

(Symmetric equations are obviously defined for the return pipes calculation in each network.)

6.2.7 Connections of nodes and implementation/location of the technologies

The following constraints have been introduced for modeling the design of the network configuration (connections), and for defining the location of the centralized and decentralized conversion technologies.

1. Network configuration
   Equations 30 and 31 define the existence of a connection between nodes i and j for networks hs and cs if energy (therefore water) flows from i to j ($\dot{M}_{\text{hs}}^{\text{ub}}$ and $\dot{M}_{\text{cs}}^{\text{ub}}$ are upper bounds computed in the data processing routine.)[5]:

$$X_{\text{hs},i,j} \cdot \dot{M}_{\text{hs}}^{\text{ub}} \geq \dot{M}_{\text{hs},t,i,j} \qquad \forall t,i,j \tag{30}$$

$$X_{\text{cs},i,j} \cdot \dot{M}_{\text{cs}}^{\text{ub}} \geq \dot{M}_{\text{cs},t,i,j} \qquad \forall t,i,j \tag{31}$$

   Equations 32 ensures that if a connection is implemented from node i to j in the heating supply network (hs) a connection is implemented from j to i in the heating return network (hr). The same is valid for the cooling network (between the supply cs and the return cr, equation 33). Equation 34 ensures that the heating and the cooling network run parallel to each other.

$$X_{\text{hs},i,j} = X_{\text{hr},j,i} \qquad \forall i,j \tag{32}$$

$$X_{\text{cs},i,j} = X_{\text{cr},j,i} \qquad \forall i,j \tag{33}$$

$$X_{\text{hs},i,j} = X_{\text{cs},i,j} \qquad \forall i,j \tag{34}$$

2. District energy conversion technologies
   Equations 35 and 36 define the node where a district technology will be implemented $X_{ht,k}$, and ensure that if the technology is operated at level $x_{ht,t}$, the heat generated by the district technology remains between the design load of the technology and the minimum technically acceptable part load κ_{ht}. Y_k^{tech} is a parameter defined in the structuring phase that defines the eligibility or not of a node to host a centralized technology. Analoguous equations are defined for the district cooling technologies.
   Heating technologies:

$$\dot{Q}_{ht,t,k}^{\text{tech}} \leq x_{ht,t} \cdot X_{ht,k} \cdot Y_k^{\text{tech}} \cdot S_{ht} \qquad \forall ht,t,k \tag{35}$$

$$\dot{Q}_{ht,t,k}^{\text{tech}} \geq x_{ht,t} \cdot X_{ht,k} \cdot Y_k^{\text{tech}} \cdot S_{ht} \cdot \kappa_{ht} \qquad \forall ht,t,k \tag{36}$$

$$\sum_k X_{ht,k} \leq 1 \qquad \forall ht \tag{37}$$

3. Sizes of the decentralized energy conversion technologies

$$\dot{Q}_{t,k}^{i} \leq S_k^{\text{i}} \qquad \forall t,k \tag{38}$$

$$X_k^{\text{i}} \cdot \dot{Q}_{H,k}^{\max} \geq S_k^{\text{i}} \qquad \forall k \in Nodes \tag{39}$$

$$X_k^{\text{i}} \cdot \dot{Q}_{H,k}^{\min} \leq S_k^{\text{i}} \qquad \forall k \in Nodes \tag{40}$$

   It should be mentioned that in order to maintain the feasibility of the slave optimization, such constraints do not concern the backup boilers but only the other decentralized units. The backup oil burners wiil therefore be used to close the energy balance at each node and its size will be determined by the slave optimisation. Obviously these units will also introduce the corresponding investment costs that will be considered in the objective function.

[5]Note that the binary variables are no indexed over the periods t since the final layout of the network is the same for all periods.

6.2.8 Costing and CO_2 emission functions

The costing functions implemented in the slave optimization include:

1. the linearized investment costs of the pipes of the distribution networks, the circulation pumps, the heat exchangers between the networks and the buildings, and the individual back-up energy conversion technologies,
2. the operating costs (including the maintenance and energy ressources: natural gas, electricity from the grid and oil for the boilers),
3. the incomes from the electricity sales.

ANNUAL INVESTMENT COSTS ESTIMATION

1. Pipes
In order to compute the investment costs for the pipes, the fixed costs are charged if a heating and/or cooling pipe is requested between two nodes ($X_{\text{hs},i,j} = 1$ and/or $X_{\text{cs},i,j} = 1$), but not yet existing ($Y^{\text{pipe}}_{\text{hs},i,j} = 0$ and/or $Y^{\text{pipe}}_{\text{cs},i,j} = 0$). If both heating and cooling pipes are requested, the fixed costs are charged only once.
$$\begin{aligned} C^{\text{pipes}} &= \frac{Ms^{\text{pipe}}}{1306.6} \cdot (1 + Fm^{\text{pipe}}) \cdot An^{\text{pipe}} \cdot \sum_{(i,j)} Dist_{i,j} \cdot \\ &\quad ((X_{i,j} \cdot C^{\text{pipe}}_{fix}) + ((A_{\text{hs},i,j} \cdot c^{\text{pipe}}_{prop}) \cdot (1 - Y^{\text{pipe}}_{\text{hs},i,j}) \cdot X_{\text{hs},i,j}) + \\ &\quad ((A_{\text{cs},i,j} \cdot c^{\text{pipe}}_{prop}) \cdot (1 - Y^{\text{pipe}}_{\text{cs},i,j}) \cdot X_{\text{cs},i,j}) \end{aligned} \tag{41}$$
with:
$$X_{i,j} \geq (X_{\text{hs},i,j} \cdot (1 - Y^{\text{pipe}}_{\text{hs},i,j})) \qquad \forall i,j \tag{42}$$
and:
$$X_{i,j} \geq (X_{\text{cs},i,j} \cdot (1 - Y^{\text{pipe}}_{\text{cs},i,j})) \qquad \forall i,j \tag{43}$$
Equations 42 and 43 to ensure that the fixed costs for the pipes only accrue if a heating and/or cooling pipe is/are required and not already existing.

Moreover:
$$A_{\text{hs},i,j} = \frac{\max_t \dot{M}_{\text{hs},t,i,j}}{v \cdot \rho} \qquad A_{\text{cs},i,j} = \frac{\max_t \dot{M}_{\text{cs},t,i,j}}{v \cdot \rho} \qquad \forall i,j$$

2. Pumps
Heating network:
$$\begin{aligned} C^{\text{pump}} &= \frac{Ms^{\text{pump}}}{1306.6} \cdot (1 + Fm^{\text{pump}}) \cdot An^{\text{pump}} \cdot \\ &\quad ((X^{\text{hn}} \cdot C^{\text{pump}}_{fix} + S^{\text{pump}}_{\text{hn}} \cdot c^{\text{pump}}_{prop}) + \\ &\quad (X^{\text{cn}} \cdot C^{\text{pump}}_{fix} + S^{\text{pump}}_{\text{cn}} \cdot c^{\text{pump}}_{prop})) \end{aligned} \tag{44}$$
with:
$$S^{\text{pump}}_{\text{hn}} = \frac{\max_t ((\dot{M}_{\text{hs},t,i,j} + \dot{M}_{\text{hr},t,j,i}) \cdot Dist_{i,j} \cdot p^{\text{drop}}_t)}{\rho} \qquad \forall i,j$$
and
$$S^{\text{pump}}_{\text{hn}} \leq X^{\text{hn}} \cdot (\dot{M}^{\text{ub}}_{\text{hs}} + \dot{M}^{\text{ub}}_{\text{cs}})$$
and symmetrically for the cooling network.

3. Heat exchangers
   The investment costs for the heat-exchangers are estimated in the data processing routine and result in the following annual investment cost:

$$C^{\text{hex}} = \frac{Ms^{\text{HEX}}}{1306.6} \cdot (1 + Fm^{\text{HEX}}) \cdot An^{\text{HEX}} \cdot \sum_k (X^{\text{HEX}}_{\text{hn},k} \cdot C^{\text{HEX\_inv}}_{\text{hs},k} + X^{\text{HEX}}_{\text{cn},k} \cdot C^{\text{HEX\_inv}}_{\text{cs},k}) \tag{45}$$

   with:

$$\dot{Q}^{\text{build}}_{\text{hs},t,k} + \dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k} \leq X^{\text{HEX}}_{\text{hn},k} \cdot (\dot{Q}^{\text{cons}}_{H,t,k} + \dot{Q}^{\text{cons}}_{HW,t,k}) \qquad \forall t, k$$

   and

$$\dot{Q}^{\text{build}}_{\text{cs},t,k} \leq X^{\text{HEX}}_{\text{cn},k} \cdot \dot{Q}^{\text{cons}}_{C,t,k} \qquad \forall t, k$$

4. Decentralized energy conversion technologies

$$C^{\text{i}} = \frac{Ms^{\text{aw}}}{1306.6} \cdot (1 + Fm^{\text{i}}) \cdot An^{\text{i}} \cdot \sum_k \left((X^{\text{i}}_k \cdot C^{\text{i}}_{fix}) + (S^{\text{i}}_k \cdot c^{\text{i}}_{prop}) \right) \tag{46}$$

   In order to account for different expected lifetimes, annuity factors are considered for each equipment according to following equation:

$$An^i = \frac{r^i \cdot (1 + r^i)^{N^i}}{(1 + r^i)^{N^i} - 1} \tag{47}$$

Operating costs
The annual operating costs are obtained by summing the operating costs in each period and considering the duration of each period.

1. Grid costs

$$C^{\text{grid}} = \sum_t \dot{E}^{\text{grid}}_t \cdot D_t \cdot c^{\text{grid}} \tag{48}$$

2. Natural gas costs

$$C^{\text{gas}} = \sum_t R^{\text{gas}}_t \cdot D_t \cdot c^{\text{gas}} \tag{49}$$

   in which:

$$R^{\text{gas}}_t = \sum_{ht} \sum_k \frac{\dot{Q}^{\text{tech}}_{ht,t,k}}{\epsilon^{ht}_{\text{th}}} \tag{50}$$

   and R^{gas}_t the average hourly gas consumption rate required by all the district energy conversion technologies operated with natural gas (no back-up device is operated with natural gas), and D_t the duration of period t in hours.
3. Oil costs (only for individual back-up boilers)

$$C^{\text{oil}} = \sum_t R^{\text{oil}}_t \cdot D_t \cdot c^{\text{oil}} \tag{51}$$

$$R^{\text{oil}}_t = \sum_k \frac{\dot{Q}^{\text{boiler}}_{t,k}}{\epsilon^{\text{boiler}}} \tag{52}$$

   with R^{oil}_t the average hourly oil consumption rate required by the boilers, if any.

Incomes

Incomes can be generated by the sale of superfluous electricity

$$I^{\text{el}} = \sum_t \dot{E}_t^{\text{sold}} \cdot D_t \cdot b^{\text{grid}} \tag{53}$$

where b^{grid} is the price paid by the grid when buying electricity.

CO_2 emissions

The CO_2 emissions are computed considering the emissions related to the overall resources used in the system, considerng the emissions of natural gas, Oil and electricity. When the net balance of electricity corresponds to an export of electricity, one may choose ${co_2}^{\text{subst}}$ to consider the substitution based on the mean value of the grid using the electricity CO_2 mix or to consider the substitution of the CO_2 emissions of a new power plant to be build.

$$C^{\text{CO}_2} = \sum_t (R_t^{\text{gas}} \cdot {co_2}^{\text{gas}} + \dot{E}_t^{\text{grid}} \cdot {co_2}^{\text{grid}} - \dot{E}_t^{\text{sold}} \cdot {co_2}^{\text{subst}} + R_t^{\text{oil}} \cdot {co_2}^{\text{oil}}) \cdot D_t \tag{54}$$

6.2.9 Considering multi-objective aspects in the slave optimization

The optimization problem decomposition should be compatible with the multi-objective optimization strategy used at the master optimization level. For the slave optimization, we have therefore introduced a parametric programming dimension by introducing a weighting factor between the terms that represent the two objectives in the slave optimization the two objectives in the slave optimization. As the two objectives are on one hand the total cost and on the other hand the CO_2 emissions, a CO_2 tax is introduced as a parameter of the slave optimization. This allows us to weight the importance of the CO_2 emissions in the slave optimization objective function. the value of the CO_2 tax is then introduced as a decision variable in the master optimization, together with the sizes of the centralized technologies and the temperatures of the networks.

6.2.10 Empirical constraints

Empirical constraints based on the experience of the engineer allow one to speed up the resolution time by reducing the search space, without excluding the optimal solution. These result from a systematic analysis of the problem statement. The slave optimization includes constraints based on heuristic rules referring to the implementation of the technologies (district technologies and back-up technologies), and the pipe routing. Unlike cuts, which are managed directly by the solver, or valid inequalities (formulated by the programmer but redundant in the problem definition), the addition of empirical constraints changes the mathematical formulation of the problem by eliminating feasible integer solutions, however only sub-optimal solutions.

Connection constraints

Heating and/or cooling cannot at a node k be provided by two different routes.

$$\sum_i X_{\text{hs},i,k} \leq 1 \qquad \forall k \in Nodes \tag{55}$$

This assumption is valid in the case of one centralized production unit. It will not be considered if more than one centralized production unit is allowed and considered in the master optimization problem.

Decentralised energy conversion technologies

No more than one back-up energy conversion technology can be implemented on a given node k to provide heating and hot water (for the cooling requirements there is anyway only one possible back-up technology, so that a constraint such as 56 is not necessary):

$$X_k^{\text{aw}} + X_k^{\text{ww}} + X_k^{\text{boiler}} \leq 1 \qquad \forall k \in Nodes \tag{56}$$

If the node is connected to the network, no air/water heat pump or boiler can be used at this same node:

$$X_k^{\text{aw}} + X_k^{\text{boiler}} + \sum_i X_{\text{hs},i,k} \leq 1 \qquad \forall k \in Nodes \tag{57}$$

Routing of the pipes

From the analysis of the possible connexions between nodes in the system, algorithms like the one used in [18] allow to identify the possible cycles. Considering the list of possible cycles in which a node is involved, the following constraints will be added in order to avoid the creation of cycles. It should be mentioned that this constraints could be updated when reliability cosntraints have to be considered.

$$\sum_{i \in cycle[c]} X_{i,next(i)} \leq card(cycle[c]) - 1; \tag{58}$$

6.3 Data pre-processing routine

The evolutionary algorithm used in the master optimization builds a "genome", the performance of which is computed by solving the slave optimization problem. In order to set up the slave problem, a data pre-processing is realised.

1. Given the values of the decision variables in the master set, the data pre-processing routine first defines the heat cascade corrected temperature intervals, evaluates the heat exchanger surfaces and costs, approximates the average specific heat and pressure losses. Applying cost estimation expressions, linearised equipment cost are also estimated for the decentralized technologies.
2. The empirical and feasibility constraints are defined. An example of inconsistency is for instance when the master optimizer defines a condenser temperature for a heat pump that is below the return temperature of the heating network, making the heat pump useless. In this case, the data processing routine doesn't pass the heat pump to the slave optimization, thus reducing its search space and avoiding the iterations that would be necessary in the slave optimization to find out that the heat pump is useless. The annual investment cost of the heat pump is nonetheless taken into account in the objective function of the master optimization. Hence the technology induces investment costs, but doesn't provide any useful energy, thus discouraging the master optimizer from choosing it. Such controls can be included for any type of district energy conversion technology, according to the specificities of the technology.
3. It defines the upper and lower bounds of the continuous decision variables of the slave optimization, that can be derived from the values given by the master optimization. Defining a more restrictive set of upper and lower bounds reduces the computation size of the search space and therefore drastically reduces the computations time.

The pre-processing phase that adds constraints and bounds allows to reduce the computation time from hours to minutes. This step is therefore of prime importance when considering that the master optimization requires several thousands of iterations to reach convergence.

Once the slave optimization has converged, the results are again processed in the post processing phase, where the non linear performances of the system are computed. From the equipment sizes proposed by the master optimisation, the investment of the centralised units is defined. From the results of the optimisation, the flows in the district heating network are known. These are used to compute the size of the pipes and deduce their "non linear" cost. The size of the decentralised units is also resulting from the slave optimisation and their cost is further computed considering non linear equations where appropriate. The cost of the heat exchangers is also re-evaluated and the annual operating cost of the system is computed together with the overall emissions.

It should be mentioned that the CO_2 emission tax is not considered when evaluating the annual operating cost, since it represents only a weighting factor for realising the parametric multi-objective optimization in the salve optimization strategy.

The following general assumptions have been considered when building the model:

1. The differences in altitude have been neglected.
2. All heat-exchangers are counter-flow heat-exchangers.
3. For the decentralized heat pumps, the condenser temperature has been chosen in function of the hot water requirements (regardless of wether the heat pump supplies heat or hot water requirements). This assumption penalizes especially low temperature heating buildings and should therefore be refined in a more detailed approach.
4. If any excess electricity is generated by the district energy conversion technologies, it can be decided from case to case, whether this electricity shall be sold to the grid or not.
5. If any excess heat or cold is generated by the district energy conversion technologies, this energy is lost to the surroundings without any investment penalty
6. Storage tanks are considered only for peak shaving and are supposed to be part of the equipment cost. This means that the mean heat demand can be used and includes compensation for heat load demand variations. It should be noted that in district heating systems, the volume of water in the pipes correspond to a significant buffer capacity.
7. Heat losses in the pipes are considered for the heating network but neglected for the cooling network, due to the relatively small temperature difference between the supply pipes and the surroundings as compared to the heating network.

7 Test case application

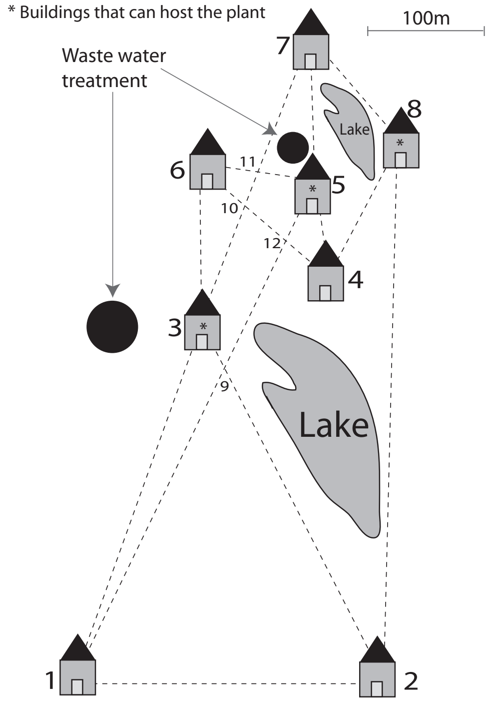
The method is applied to the test example presented of figure 6.

The goals of the study is to design the energy conversion system that will provide heating, hot water, cooling and electricity to a district of 8 buildings considering the minimization of the yearly CO_2 emissions and costs. The district to be developed (figure 6) is supposed to be new, so that no equipment is existing beforehand, except for the electricity grid. The dashed lines in figure 6 show the connections which are allowed between buildings and/or crossings (nodes).

7.1 Structuring of the information

According to the method, the following information is gathered and structured:

List of available energy sources
Regarding the energy sources, two types of renewable energy sources can be used, namely two lakes and



	Heating kWth	Hot water kWth	Cooling kWth	Elec-tricity kWel
1	500	35	200	125
2	350	30	350	86
3	470	30	86	150
4	600	55	300	150
5	580	55	300	125
6	500	40	100	110
7	300	35	150	86
8	340	30	75	80
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0

Figure 6: District analysed, with the maximum requirements in kW for each energy service and the buildings that can host the plant with the district energy conversion technologies

Period	Duration		T^{atm}	
summer day	1095	hr/year	25	°C
summer night	1095	hr/year	15	°C
mid-season day	2190	hr/year	14	°C
mid-season night	2190	hr/year	10	°C
winter day	1095	hr/year	1	°C
winter night	1095	hr/year	-5	°C

Table 2: Periods considered in the test case with their duration and average atmospheric temperature

two wastewater treatment facilities that can provide energy to heat pumps. Regarding the non renewable sources, natural gas is the only one that is considered, since heating oil has been left out for centralized production. Other sources such as waste incineration or biomass have been assumed not to be available.

Energy consumption profiles including power and temperature levels

The energy consumption profiles have been developed. Six representative periods have been defined with their relative duration in hours/year, and average atmospheric temperature. These periods are defined in table 2. As already mentioned, since the purpose of the method is the *design* of a district energy system, and not the *controlling* of this system, it has been considered sufficient to divide the whole year into 6 periods only. This simplification has the disadvantage to exclude days with extreme weather events and could therefore favour undersized equipment. Increasing the number of representative periods however would lead to an increased number of variables and therefore an increase of the computation time required to solve the slave optimization problem. The analysis of the solutions with more detailed simulations will show the feasibility or not of the solutions proposed, for extreme conditions. In case the solutions are penalising, extreme periods could be added to the period set as shown in [26].

The consumption profiles are presented in figures 8 to 10. The temperature levels for the heating require-

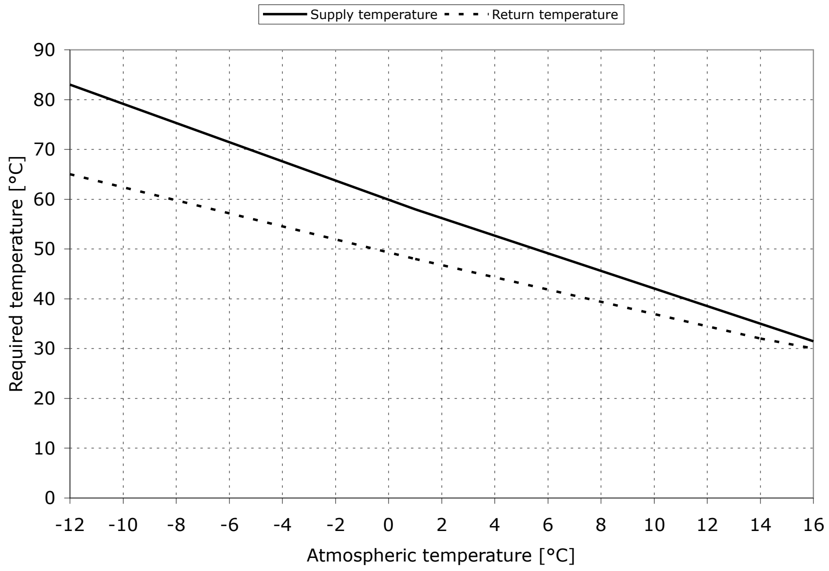


Figure 7: Heating supply and return temperatures of the hydronic circuit of the buildings [13]

ments, corresponding to the supply temperature T_S and the return temperature T_R of the hydronic circuit in the building, have been set to $T_S = 35°C$ and $T_R = 32°C$ for the mid-season periods and $T_S = 58°C$ and $T_R = 48°C$ for the winter periods, according to figure 7. The water used for the hot water requirements (figure 9) has been assumed to enter the buildings at 10°C and a set point of 60°C. Finally for the cooling requirements (figure 10), the temperatures have been set for all the buildings to $T_S = 18°C$ and to $T_R = 21°C$. These latter values, which are higher than what is usually admitted ($T_S = 6°C$ and to $T_R = 12°C$) have been estimated based on what could be found in modern installations [29].

Comparing the list of available energy sources together with the energy service requirements of the district including the temperature and power levels of these requirements, the following technologies are considered as reasonable and taken up in the list of possible district energy conversion technologies. The resulting energy conversion superstructure is presented in figure 12.

1. Heating and hot water:
   - A heat pump, connecting the return pipe of the cooling network on the evaporator side with the supply pipe of the heating network on the condenser side. This heat pump thus allows the energy transfer between the buildings requiring cooling and the buildings requiring heating. This heat pump will be abbreviated HP1 in the following, its lower bound is 1 000 kWth and its upper bound 5 000 kWth.
   - A second heat pump, valorizing energy from the lake(s) and having therefore its evaporator temperature determined by the temperature of the lake. A maximum temperature difference of 4°C is assumed in the evaporator for the water coming from the lake, in order to avoid freezing in winter (the temperature of the water in the lake being 6°C). This heat pump will be abbreviated HP2 in the following, its lower bound is 1 000 kWth and its upper bound 5 000 kWth.
   - A third heat pump, converting energy recycled from the wastewater treatment facility(ies) and having therefore its evaporator temperature determined by the temperature of the wastewater

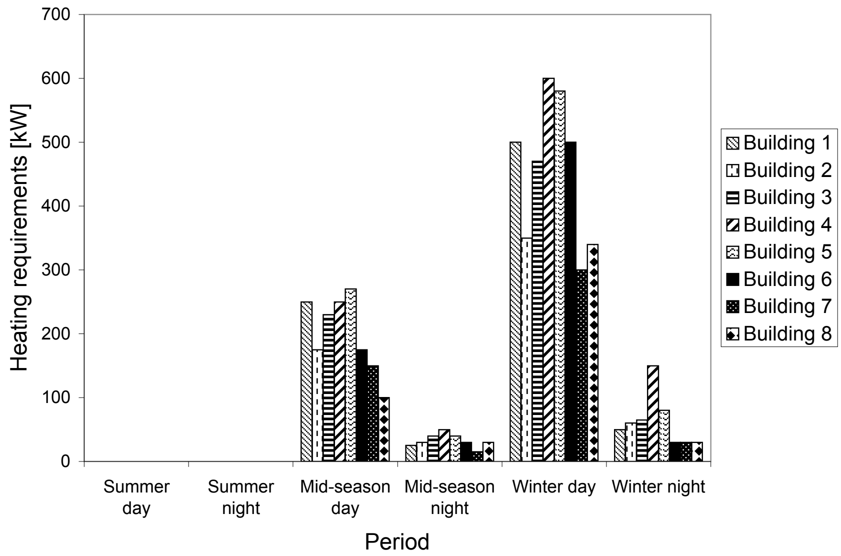


Figure 8: Heating requirements of the buildings in the district for the different periods

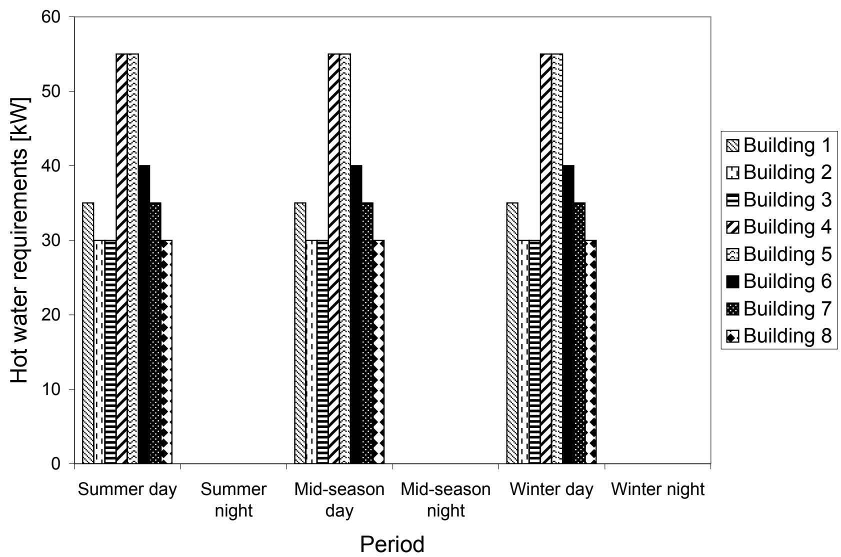


Figure 9: Hot water requirements of the buildings in the district for the different periods

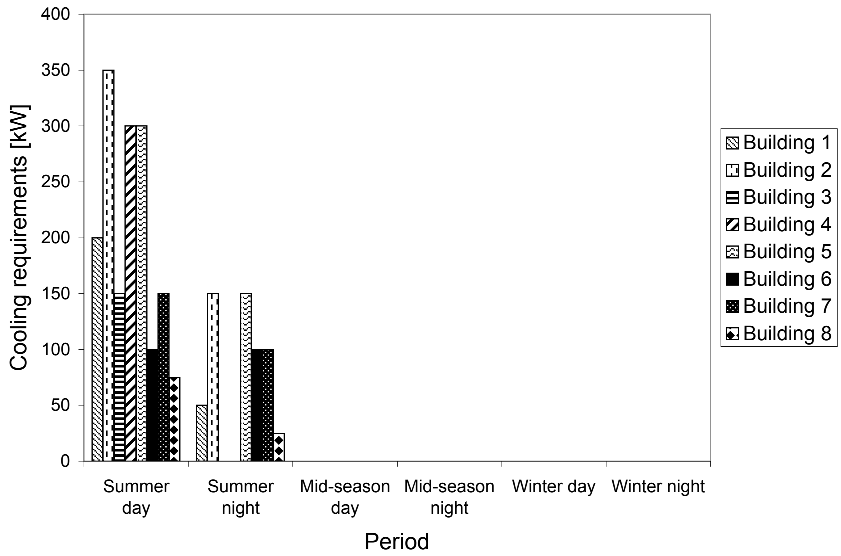


Figure 10: Cooling requirements of the buildings in the district for the different periods

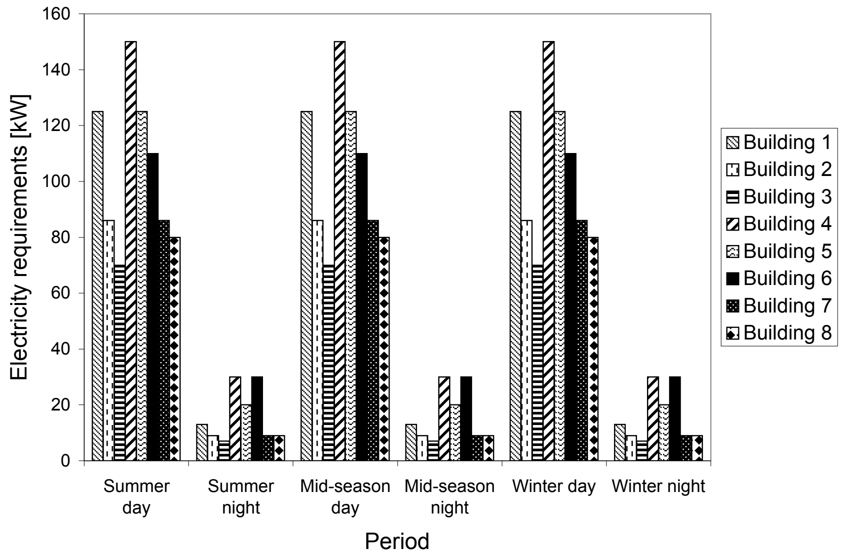


Figure 11: Electricity requirements of the buildings in the district for the different periods

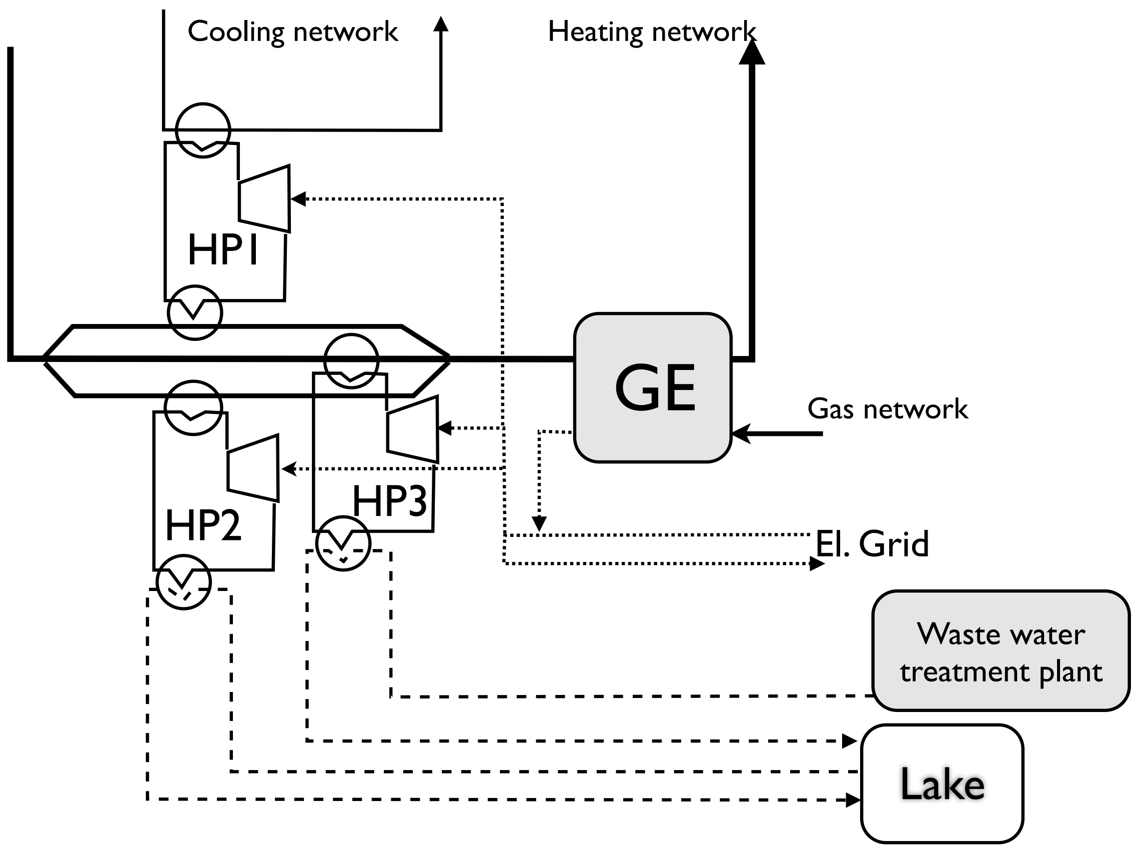


Figure 12: Superstructure of the energy conversion system for the test case

Parameter	Summer	Mid-season	Winter
Temperature of the lakes °C	8	6	6
Temperature of the municipal wastewater treatment facility in summer °C [3]	22	18.5	16

Table 3: Temperature level of the lake and the wastewater treatment facility

treatment facility(ies): 16°C in winter, 18.5°C during the mid-seasons and 22°C in summer. As mentioned in section 6.3, a temperature difference of 10°C is assumed in the evaporator for the water coming from the wastewater treatment facility. This heat pump will be abbreviated HP3 in the following, its lower bound is 1 000 kWth and its upper bound 5 000 kWth.

2. Cooling:
    - The HP1 heat pump mentioned above, allowing heat pumping from the cooling return pipe.
    - "Free" cooling using water from the lake(s) that is being circulated through the district network.
3. Combined heat and power:
    - A gas engine (abbreviated GE), used in cogeneration mode, with a lower bound at 1 000 kWel and an upper bound at 5 000 kWel.

For the lake(s) and the wastewater treatment facility(ies), it is assumed that the resources are unlimited. In a more detailed analysis (for instance if HP2 or HP3 type heat pumps appear to be promising technologies), the temperature difference of 4°C, respectively 10°C, assumed in the evaporator, should also be optimized. In this case however, the mass flow rate between the lake or the wastewater treatment facility(ies) and the heat pump, should also be considered. Besides, a limited amount of water could easily be taken into account by setting a constraint on the energy source. The temperature levels for the lake and the wastewater treatment facility are given in table 3

Spatial constraints and possible connections

Possible location of the district energy conversion technologies (figure 6): only buildings 3, 5 and 8 are possible candidates. Besides, the possible connections obtained from a routing algorithm, are given as dotted lines on figure 6. Other than this, no size related constraints are given.

Decentralized technologies

As decentralized technologies, air/water and water/water heat pumps as well as boilers for heating and hot water, electric chillers for cooling have been considered. In order to compute the annual investment costs, the parameters given in table 4 have been used. Besides, the efficiencies given in table 5 have been used.

Parameter	Range	Value	Unit	Reference
C_{fix}^{pipe}	0-300 mm ø	753	CHF	[19]
c_{prop}^{pipe}	0-300 mm ø	7	CHF/m	[19]
C_{fix}^{boiler}	100-650 kWth	1000	CHF	[14]
c_{prop}^{boiler}	100-650 kWth	218	CHF/kWth	[14]
C_{fix}^{aw}	100-650 kWth	1000	CHF	[28]
c_{prop}^{aw}	100-650 kWth	1890	CHF/kWth	[28]
C_{fix}^{ww}	350-650 kWth	42833	CHF	[8]
c_{prop}^{ww}	350-650 kWth	126	CHF/kWth	[8]
C_{fix}^{chiller}	0-350	2500	CHF	Eval. after [8]
$c_{prop}^{\text{chiller}}$	0-350 kWth	2835	CHF/kWth	Eval. after [8]
r^i	$i = aw, boiler, chiller, hex, pipes, pump, ww$	0.08		[9]
F_m^i	$i = aw, boiler, chiller, hex, pipes, pump, ww$	0.06		[9]
M_S^i	year 2006 ($i = aw, boiler, chiller, ww$)	1306.6		[9]
M_S^i	year 1998 ($i = hex, pipes, pump$)	1306.6		[9]

Table 4: Parameters for the costing functions in the test case

Parameter	Value	Units	Reference
Exergetic efficiency of the individual back-up air/water heat pumps	0.34	[-]	[13]
Exergetic efficiency of the individual back-up water/water heat pumps	0.4	[-]	[13]
Exergetic efficiency of the individual back-up chillers	0.19	[-]	after [7]

Table 5: Efficiency parameters related to the individual back-up technologies, used in the test case

8 Optimization

8.1 Decision variables

The master optimizer optimizes 17 decision variables:

1. Supply and return temperatures of the heating network in summer, and winter/mid-seasons: variables 1 to 4
2. Supply and return temperatures of the cooling network in summer (no cooling is assumed during the winter and the mid-seasons): variables 5 and 6
3. Investment or not in a HP1, HP2 and HP3 as well as gas engine GE: variables 7 to 10
4. Design size of heat pumps HP1, HP2 and HP3 as well as gas engine GE: variable 11 to 14
5. Condenser temperature of heat pumps HP1, HP2 and HP3: variable 15 to 17

Beside these decision variables, the master optimization also defines the CO_2 weighting factor. The condenser temperatures of the heat pumps don't necessarily equal the supply temperature of the heating network, as the three heat pumps and the gas engine can be put in series. In fact, in an optimally integrated system these energy conversion technologies *will* be in series, in order for the heat pumps to operate at better COPs. This will be computed in the heat cascade model.

All the parameters used for the test case are given in tables 4 to 6.

Parameter	Value	Units	Reference
CO_2 emissions of electricity from the grid $co_2{}^{\text{grid}}$ (european mix)	0.450	[kg/kWh]	[10]
CO_2 emissions for natural gas $co_2{}^{\text{gas}}$ (including transportation)	0.230	[kg/kWh]	[10]
CO_2 emissions for heating oil $co_2{}^{\text{oil}}$ (including transportation)	0.293	[kg/kWh]	[10]
Cost for electricity from the grid c^{grid}	0.13	[CHF/kWh]	[4]
Cost for natural gas c^{gas}	0.04	[CHF/kWh]	[4]
Cost for heating oil c^{oil}	0.0645	[CHF/kWh]	[4]
Efficiency of the circulation pumps	80%	[-]	
Friction coefficient in the pipes λ	0.02	[-]	[19]
Grid efficiency ϵ^{grid}	90%	[-]	
Heat transfer coefficent in the pipes K	0.203	[W/mK]	[19]
Isobaric specific heat of water $cp^{\text{liq}}_{H_2O}$	4.178	[kJ/(kg K)]	
Overall heat transfer coefficient in heat exchangers	800	[W/(m2 K)]	[6]
Minimum ΔT in the heat-exchangers between the district networks and the hydronic circuit of the buildings	2	[°C]	
Selling price of electricity b^{grid}	0.09	[CHF/kWh]	[4]

Table 6: Values of the thermodynamic and distributed energy related parameters, used in the optimization phase in general

8.1.1 Conditions defined for the optimization

To perform the optimization, it was decided that the excess electricity generated by the gas engine could be sold at a price of 0.09 CHF/kWhel [4]. However, the avoided CO_2 when selling electricity to the grid, has not been accounted when evaluating the CO_2 emissions.

8.1.2 Resolution phase analysis

According to the values chosen by the master optimizer and the subsequent data processing performed by the data processor, the number of variables optimized by the slave optimizer ranges from 35 000 to 50 000 continuous variables and from 250 to 850 binary (0-1) variables. The large number of variables optimized by the slave optimizer is due to the number of indices for each type of variable. Let's analyse for instance the variable characterizing the energy streams between nodes in the network. For the slave optimizer, there are as many variables as there are possible combinations of connections (between two nodes), periods, temperature intervals[6] and sub-networks[7]:

Number of possible connections in the test district:	21
Number of periods:	6
Number of temperature intervals:	∼20
Number of sub-networks:	4

In other words, there are $21 \cdot 6 \cdot 20 \cdot 4 = 10\,080$ decision variables only for the energy streams. The same number of decision variables are related to the mass flows.

[6]The exact number of temperature intervals describing the whole system (the highest temperature being for instance the temperature of the heat from the gas engine and the lowest temperature the supply temperature of the cooling network) depends strongly on the set of variables defined by the master optimizer.

[7]Supply and return networks for both heating and cooling.

17 000 iterations of the master optimizer have been computed. Solving this problem took 4 days 8 hours and 29 minutes of computation time on 4 Intel Pentium4 2'800 MHz computers (the resolution has been parallelized on 4 computers). The optimization time indicated here is of course strongly dependent on the number of iterations done by the master optimization[8] but also on the tolerance that the MILP solver considers **??**.

PARETO OPTIMAL FRONTIER

The results of the optimization are shown on the Pareto curve of figure 13. The most interesting configurations are summarized in table 7. In this table, the indices a and b for the heat pump HP3 refer to the two heat pumps that are implemented in series at the wastewater treatment facility, due to the high temperature difference occuring at the evaporator side. When the temperature decrease of the heat source on the evaporator side exceeds 4°C indeed, two smaller heat pumps are implemented in series instead of one large heat pump. From the Pareto optimal frontier, three distinct groups of configuration types (hereafter clusters) can be recognised:

Cluster 1 "HP3+GE+Lake" : The HP3 heat pump is implemented together with the gas engine , providing heating, hot water and electricity to all the buildings. The cooling is provided by the water from the lake supplied to all the buildings.

Cluster 2 "HP2+GE+Lake" : The HP2 heat pump is implemented together with the gas engine , providing heating, hot water and electricity to all the buildings. The cooling is provided by the water from the lake to all the buildings.

Cluster 3 "GE+Lake" : Only the gas engine is implemented to provide heating, hot water and electricity to some or all of the buildings. The cooling is provided by the water from the lake to all the buildings. No district heat pumps are implemented in this cluster.

The reference configuration, called "Initial", getting the electricity from the grid, heating and hot water from a boiler, and cooling from an electric chiller, doesn't appear on figure 13. Actually, such a configuration would emit 5 779 tons-CO_2/year and cost 1.98 mio-CHF/year, thus overshooting the cost axis of the figure, and performing poorly in terms of CO_2 emissions.

The optimal configuration in terms of CO_2 emissions (configuration 1A1 on figure 13 and table 7) emits 3 407 tons-CO_2/year (59% of the "Initial" configuration) and costs 1.49 mio-CHF/year (75% of the "Initial" configuration). This configuration features a HP3 type district heat pump, together with a gas engine, a cooling network with water from the lake, and takes the electricity partly from the grid (summer periods as well as all the night periods) and partly from the gas engine (mid-season and winter day periods). All the buildings are connected to the networks, be it for cooling or for heating and hot water. The networks are shown in figure 14.

The optimal solution in terms of annual costs (configuration 3A2 on figure 13 and table 7)emits 10 769 tons-CO_2/year and costs 1.22 mio-CHF/year. This solution features a gas engine that delivers heating and hot water to all the 8 buildings, with lake cooling for all the buildings, and electricity from the grid during the summer night period (in all the other periods, the gas engine generates enough electricity for the district and even sells some to the grid). The heating and cooling networks are shown in figure 15. Due to the way of accounting for the CO_2 emissions, this configuration emits more CO_2 than the "Initial" configuration (186%). Since the avoided CO_2 of the grid electricity production is not accounted, such solutions will emit more CO_2 than the reference. When the avoided CO_2 is accounted, such solutions become better than the present "initial" solution.

[8]The number of iterations is estimated empirically. The iterations are stopped when no improvement can be obtained from further iterations.

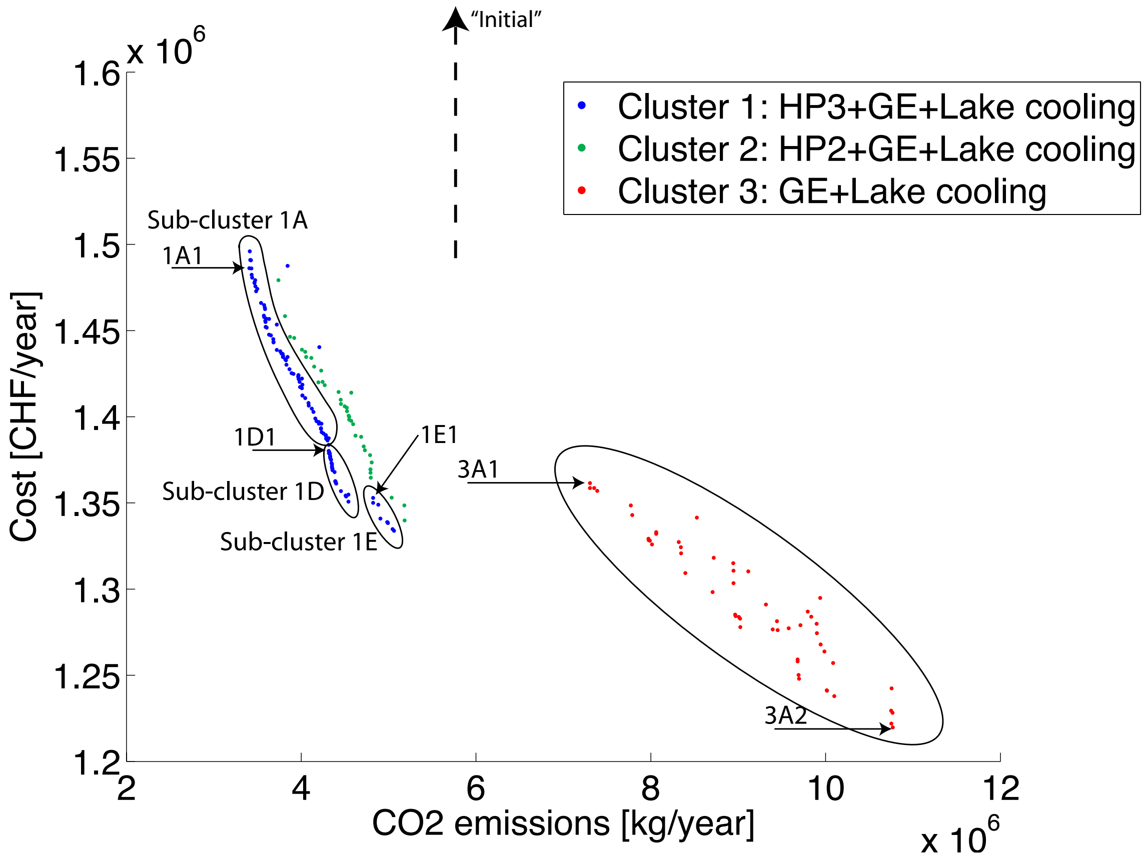


Figure 13: Pareto optimal frontier

Configuration	1A1	1A2	1B1	1D1	1E1	3A1	3A2
Annual CO_2 emissions ton-CO_2/year	3 407	4 256	3 582	4 350	4 824	7 303	10 769
Costs mio-CHF/year	1.49	1.39	1.46	1.37	1.35	1.36	1.22
Percentage Investment	53	46	53	46	44	27	22
Operational	47	54	47	54	56	73	78
Income I^{el}mio-CHF/year	0	0.18	0	0.22	0.26	0.44	1.2
Grid mio-CHF/year	0.28	0.26	0.14	0.26	0.13	0.02	0.02
Gas mio-CHF/year	0.42	0.58	0.54	0.6	0.76	1.26	1.86
HP3a Size MWth	1029	639	1040	634	634	0	0
Inv. CHF/year	174 816	123 469	176 134	122 901	122 901	0	0
T_{cond} °C	75	80	79	80	77	-	-
COP summer	3.06	3.03	3.05	3.03	3.04	-	-
COP mid-season	2.91	2.89	2.90	2.89	2.90	-	-
COP winter	2.82	2.79	2.80	2.79	2.81	-	-
HP3b Size MWth	1029	639	1040	634	634	0	0
Inv. CHF/year	174 816	123 469	176 134	122 901	122 901	0	0
T_{cond} °C	80	85	84	85	82	-	-
COP summer	3.10	3.08	3.09	3.08	3.09	-	-
COP mid-season	2.95	2.93	2.94	2.93	2.94	-	-
COP winter	2.86	2.83	2.84	2.83	2.84	-	-
GE Size MWel	1753	2532	1731	2540	2540	1978	3857
Inv. CHF/year	190 444	239 621	188 987	240 101	240 101	205 363	311 681
ϵ_{el} %	42.88	43.47	42.86	43.47	43.47	43.08	44.14
ϵ_{th} %	47.12	46.53	47.14	46.53	46.53	46.92	45.86
Lake cooling kWth	1 625	1 625	1 625	1 625	1 625	1 625	1 625
Network Inv. CHF/year	192 121	187 630	199 014	189 293	190 908	176 933	186 590
Pumps Inv. CHF/year	5 624	5 493	5 813	5 542	5 661	4 324	5 683
$T_{hs,t}$ °C Summer	70.4	71.9	68.5	72.4	110.6	103.2	94.7
Mid-season and winter	77.0	77.6	75.9	77.6	77.5	98.0	103.0
$T_{hr,t}$ °C Summer	36.4	49.0	49.4	53.2	53.2	58.1	88.9
Mid-season and winter	52.6	50.1	51.8	51.5	51.5	51.7	53.5
$T_{hs,t} - T_{hr,t}$ °C Summer	34.0	22.9	19.1	19.2	57.4	45.1	5.8
Mid-season and winter	24.4	27.5	24.1	26.1	26.0	46.3	49.5
$T_{cs,t}$ °C $\forall t$	10.2	10.0	11.0	10.0	10.0	10.5	10.2
$T_{cr,t}$ °C $\forall t$	18.9	18.9	19.0	18.8	18.8	17.0	18.9

Table 7: Main configurations for the test case

Figures 16 and 17 show for each period the composite curves for the district heating system for these two configurations (note that the scale for the X-axis changes according to the period). On the plots, the hot composite curve represents the heat provided by the district energy conversion technologies, and the cold composite curve the heat required by the district. Note that the periods during which the gas engine is not operated can be easily recognised on these figures, since no high temperature heat (up to 570°C) is generated (for instance during period 1, the summer day period, of configuration 1A1). The least CO_2 emitting configuration features also the better energetic integration. For configuration 1A1, the entire heat is provided by the heat pump during periods 1 (summer day period) and 4 (mid-season night period). Due to the constraint that the heat pump cannot be operated less than 20% of the time (to avoid shutting the heat pump on and off for a few minutes only), the heat pump generates more heat than required during these two periods. In a more refined optimization, this constraint should be analysed considering a higher number of period, including the heat storage aspects and considering more detailed models for the technologies.

It is noteworthy that in clusters 1 and 2, *all* the buildings are connected to both the heating and the cooling networks. In cluster 3, even if the heating network doesn't always connect all the buildings, the cooling network does provide cooling to all the buildings. Regarding the cooling network supply and return temperatures, one can see from table 7 that they almost always correspond to the minimum, respectively maximum, allowed temperatures. For the supply temperature, 10°C indeed corresponds to the temperature of the lake (8°C) plus the minimum temperature difference of 2°C, and for the return temperature, 19°C correspond to the return temperature of the hydronic cicruits in the buildings (21°C) minus the minimum temperature difference of 2°C. This fact is not surprising, since the heat "gains" (the opposite of the heat losses for heating networks) have been neglected and therefore advantage is taken of the maximum possible temperature difference between the supply and return pipes, in order to minimize the water that needs to be pumped. Finally, for all the configurations, an interaction between the district and the grid is always present, be it to buy or to sell electricity.

To be Pareto optimal, the configurations implementing district heat pumps need to have a heat pump using the waste water treatment plant. The configurations of cluster 2, "HP2+GE+Lake", are never Pareto optimal. This is a consequence of the low temperature heat source being at a higher temperature level for HP3 (wastewater treatment facility) than for HP2 (lake), resulting in a better COP for HP3 compared to HP2. It might appear surprising that the difference of the results between clusters 1 and 2 is not larger. The main explanation lies in the fact that the COP difference for both types of heat pumps are less than 5%.

The district heat pump HP1 is never used. This is due to the tight constraints set on this technology. *District* cooling can indeed be provided either by this heat pump or by circulating water from the lake. For both options, pipes and a circulating pump need to be implemented, so that no difference exists between the two options at this level. However, HP1 generates an investment in the technology, which water from the lake doesn't require[9]. Besides, HP1 can only be used if in parallel with the cooling requirements, heating or hot water requirements are to be satisfied. In the case analysed, this occurs only during the summer day period, for which cooling requirements and hot water requirements are to be satisfied simultaneously. Therefore if HP1 was implemented during the summer day period, another cooling technique should be sought for during the summer night period, making the overall resulting system for both periods less profitable than having only one cooling system.

8.1.3 Space restrictions

Developing district energy systems in existing cities can be made difficult due to the lack of available space in existing underground channels. In order to demonstrate how the slave optimizer integrates the space restriction constraints of and how this affects the result, a size restriction has been added to the network presented in figure 14. The resulting diameter between node 5, where the district technologies are implemented, and

[9] The costs for the heat exchanger between the lake and the network have been neglected.

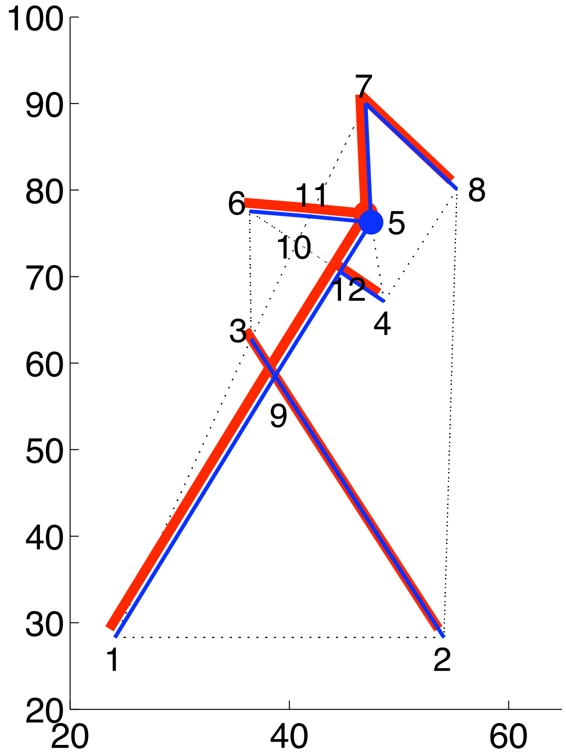


Figure 14: Cooling network (blue), heating and hot water network (red) for configuration 1A1 (see figure 13 and table 7)

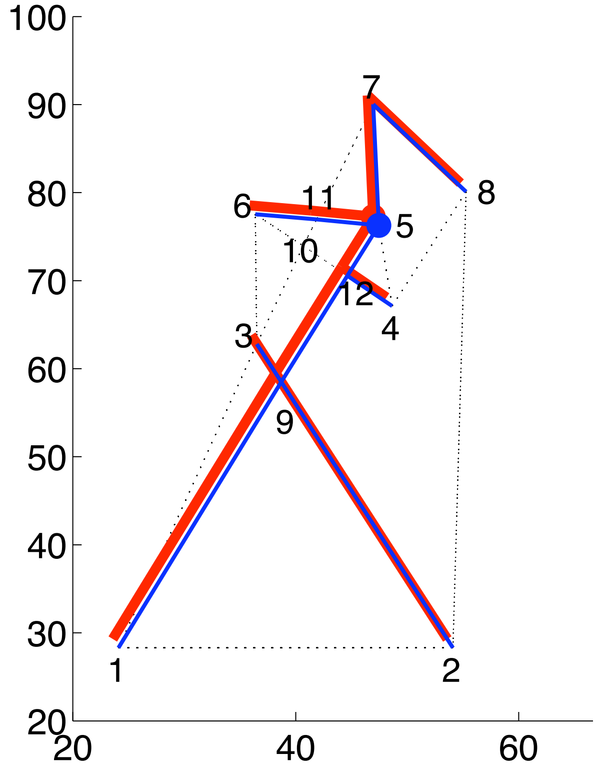
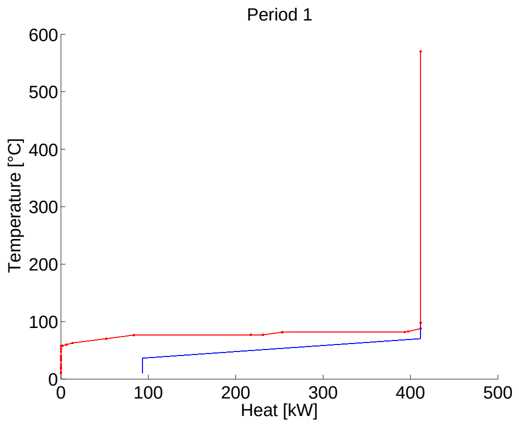
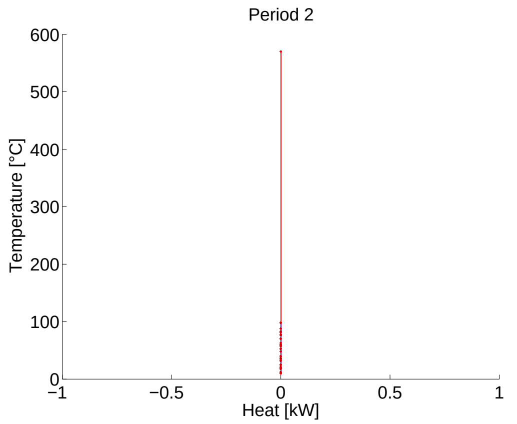


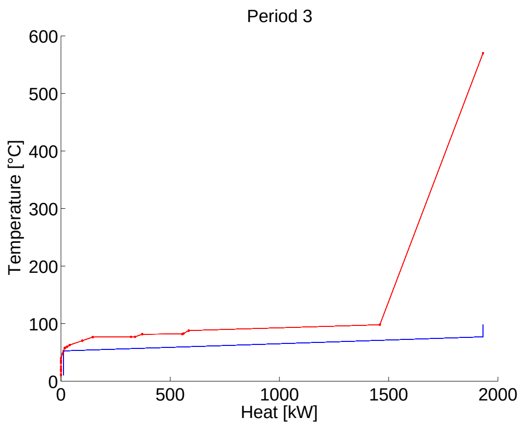
Figure 15: Cooling network (blue), heating and hot water network (red), for configuration 3A2 (see figure 13 and table 7)



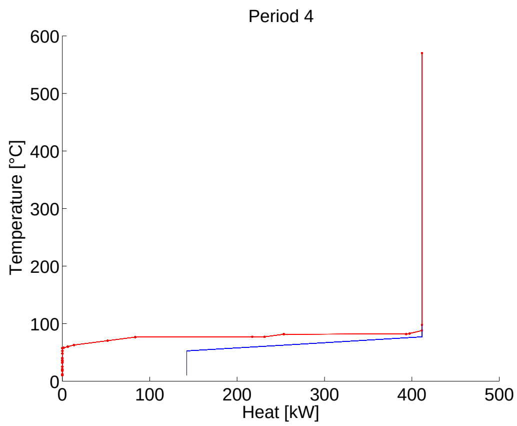
Composite curve of the summer day period



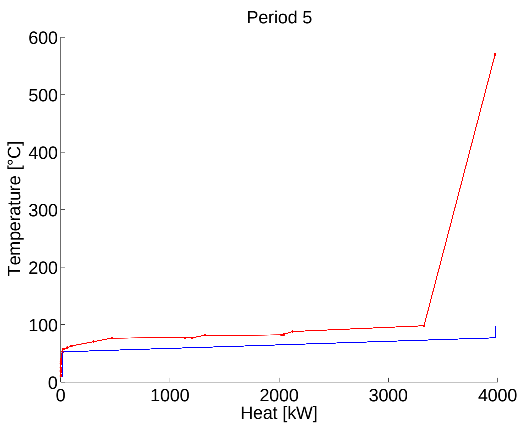
Composite curve of the summer night period



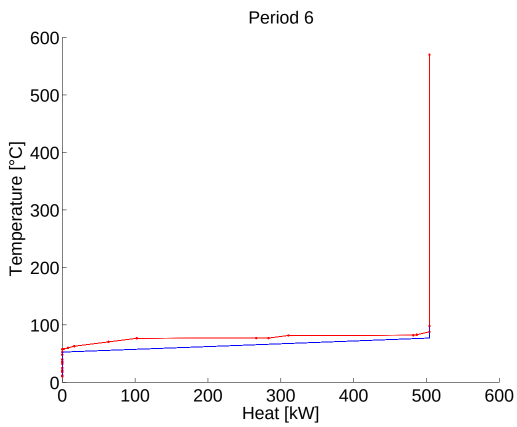
Composite curve of the mid-season day period



Composite curve of the mid-season night period

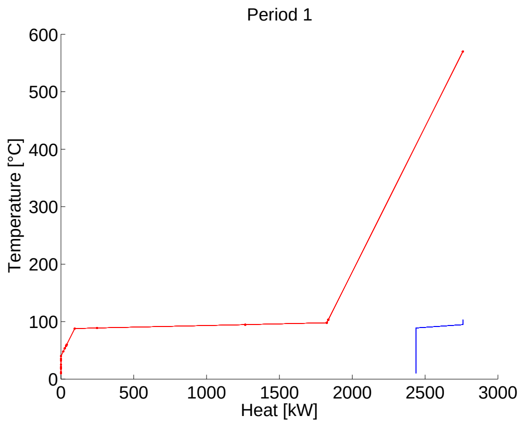


Composite curve of the winter day period

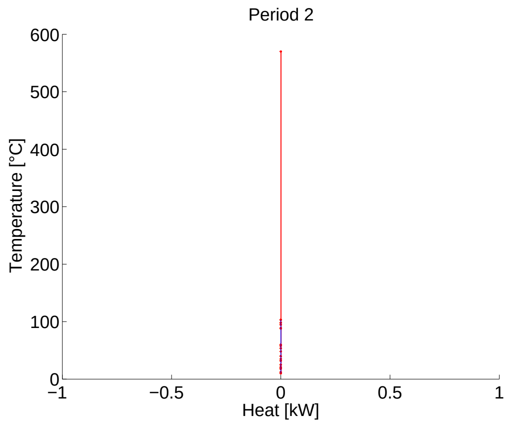


Composite curve of the winter night period

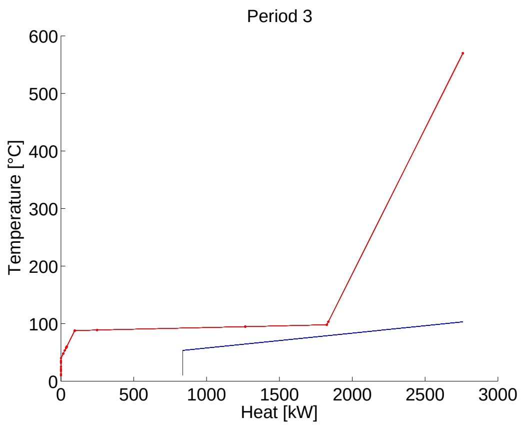
Figure 16: Composite curves for the heating and hot water requirements of configuration 1A1 (see figure 13 and table 7)



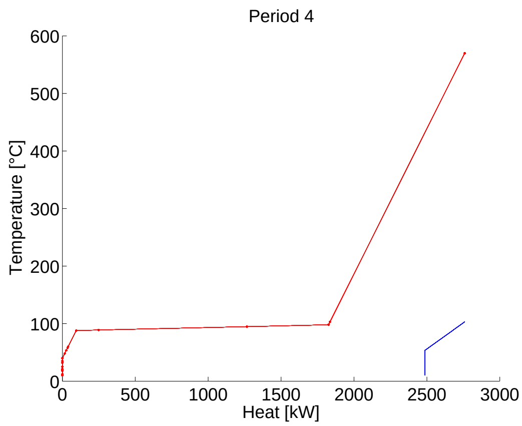
Composite curve of the summer day period



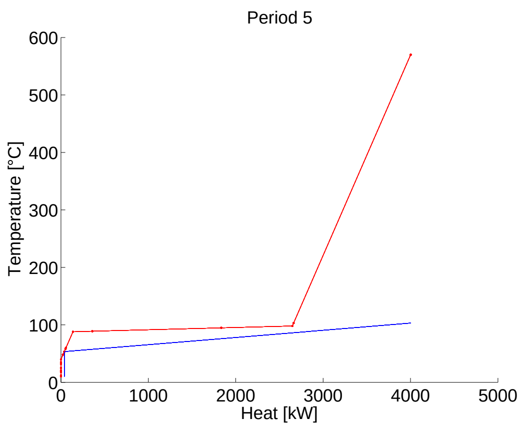
Composite curve of the summer night period



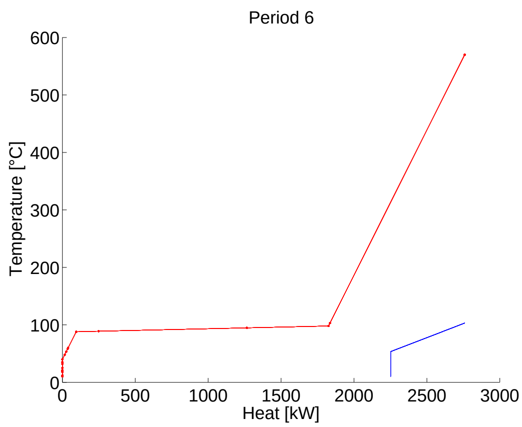
Composite curve of the mid-season day period



Composite curve of the mid-season night period



Composite curve of the winter day period



Composite curve of the winter night period

Figure 17: Composite curves for the heating and hot water requirements for configuration 3A2 (see figure 13 and table 7)

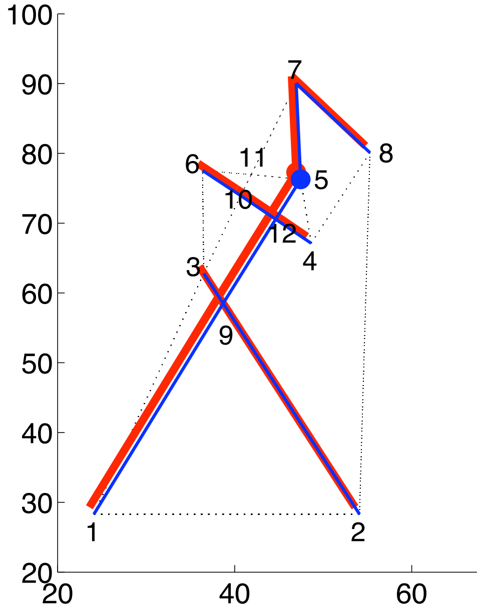


Figure 18: Resulting network from the slave optimization, with the same input from the master optimization as for configuration 1A1 but whith a size restriction imposed betweeb buildings 5 and 11

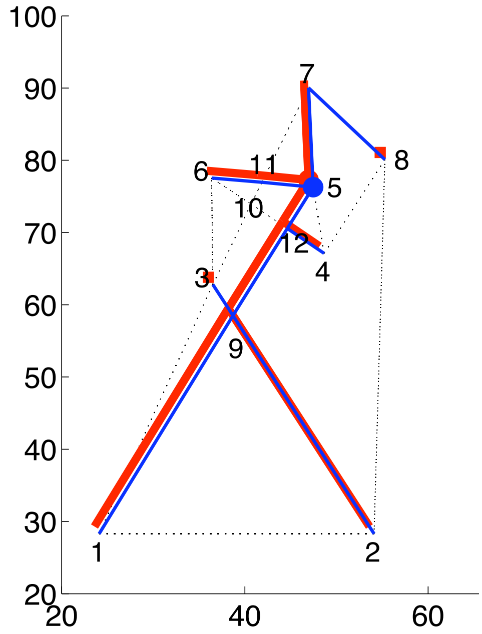


Figure 19: Resulting network from the slave optimization, with the same input from the master optimization as for configuration 1A1 but with buildings featuring requirements with different temperature levels

node 11, is 63 mm for the heating network and 112.4 mm for the cooling network. Figure 18 shows the new resulting network obtained when a maximum diameter of 10 mm is allowed between nodes 5 and 11 of the heating network. The slave optimizer has redesigned the configuration of figure 14 diverting the network over nodes 12 and 10. The size restriction on the pipe of the heating network also affects the cooling network (the shape of the cooling network is different between figure 18 and figure 14). This is explained by the fact that it is cheaper to have both networks running in parallel (only one gallery needs to be dug for both) than to have different routes for each network. For this new configuration, the investment costs amount to 193 787 CHF/year (compared to 192 121 CHF/year for configuration 1A1), and 5 738 CHF/year for the pump (compared to 5 624 CHF/year for configuration 1A1).

8.1.4 Inhomogeneous requirements

For the test case analysed in the present chapter, the buildings feature similar temperature levels for all the thermal energy requirements. It is therefore not a big surprise that all the buildings are connected to the heating (and cooling) networks in clusters 1 and 2. Figure 19 shows the resulting network for the same district, but with less homogeneous temperature levels. To compute the network of figure 19, the slave optimizer got the same input from the master optimizer as for configuration 1A1, but with following changes regarding the temperature levels of the heating and hot water requirements:

- The supply and return temperatures for the heating requirements in buildings 3 and 8 have been increased for periods 5 and 6 (winter periods) from $T_S = 58°C$ to $T_S = 70°C$ and from $T_R = 48°C$ to $T_R = 55°C$.
- In buildings 1 and 2, the temperature levels for the hot water requirements have been decreased from 60°C to 40°C, which would be enough for buildings having no showers for instance (office buildings).

From figure 19 one can see that since nothing changed for the temperature levels of the cooling requirements, the cooling network remains the same. However, the new heating network doesn't serve buildings 3 and 8. Due to their higher temperature levels, they now have their own boilers (and not heat pumps, due to the high temperature levels).

8.2 Post-processing phase

Once the Pareto optimal frontier has been computed, the most interesting options in terms of CO_2 emissions and cost are known. In order to choose which configuration will finally be implemented, the decision makers have to perform a multi-criteria analysis which will be specific to their situation. For instance if the priority is to decrease the CO_2 emissions, the least emitting configuration will be chosen. On the other hand, various "what if..." scenarios can also be tested. Or until what point would the centralized generation of heating and cooling still be an environmentaly interesting solution, if the reverse individual heat pumps become popular? How much more are the consumers of a district willing to pay in order to get a more environmental friendly energy service provider? The answers to these questions will restrict the choice to a limited number of solutions which will then have to be refined with more detailed models, and why not a more accurate division of the year in periods.

9 Conclusions

A methodology for designing urban system energy conversion system has been presented. It allows one to consider the integration of polygeneration energy conversion technologies as well as the design of heat and cold distribution network(s). Given a district with its buildings and energy consumption profiles, the method answers the following questions

1. which type of polygeneration energy conversion technologies are best suited for the district?
2. where in the district shall these technologies be implemented (geographically)?
3. Is there an opportunity or combining several technologies in an integrated system ?
4. what are the optimal supply and return temperatures of the distribution networks (heating and cooling), considering the requirements of the district and the technical limitations of the technologies?
5. how shall the buildings be connected?
6. what are the local renewable energy resources that can be valorised by heat pumping ?

The methods integrates the following aspects :

1. Thermodynamic: joint consideration of the different energy services, allowing for the implementation of efficient polygeneration energy conversion technologies, as well as in the consideration of the *temperature levels* at which the thermal energy requirements have to be satisfied, thus allowing for an optimal system integration.
2. Mathematical programming and optimisation: combination of different types of optimization algorithms, implementing each algorithm to optimize the variables it is best suited for. The optimization phase is therefore divided in a master and a slave optimization, following mathematical and hierarchical decomposition strategies. The use a multi-objtecive optimisation allows one to have a better understanding between the cost of energy and the CO_2 mitigation options.
3. Conceptual design: Integration of time and space related constraints in a same problem.
4. Modularity: Possibility of designing energy systems for very different types of districts (different location, levels of requirements, building types,...) including very different types of technologies.

5. Multiscale : The method can be used to study small district problems with a limited number of building or larger problems considering district heating substations as nodes for large scale district heating systems.

An important result of the method to help answering the questions mentioned above is a Pareto optimal frontier showing the trade-offs between the CO_2 emissions and the costs for different configurations applying to the analysed district. It includes a list of configurations which key performances indicators are computed and in which the stakeholders will choose the best system configuration applying multi-criteria analysis.

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